Interrelationships between significant tools and technologies developed in ancient Egypt: indications of an adeptly organized, expanding industrial economy, which influenced the direction, pace and structure of social evolution

A thesis submitted to the University of Manchester for the degree of
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Denys Allen Stocks, Master of Philosophy, Post Graduate Certificate in Education, Certificate in Egyptology (with distinction)

Contents

Abstract

Name of University: The University of Manchester
Candidate's full name: Denys Allen Stocks
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Title of the submission: Interrelationships between significant tools and technologies developed in ancient Egypt: indications of an adeptly organized, expanding industrial economy, which influenced the direction, pace and structure of social evolution.
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This thesis contains experimental research into ancient Egyptian technology, incorporated within twenty-two publications.

The manufacture, test, analysis and evaluation of over two hundred replica and reconstructed tools identified important interrelationships between vital tools, and their associated manufacturing processes, which played a central rôle in the development of Egyptian technology, and Egypt's social evolution.

Summarized below are the contents of the thesis:

The conversion of four specific flint tools' shapes into five edged copper tools.

The cutting abilities of copper, bronze, iron and flint chisels and punches.

The modification of the reed tube into a furnace blowpipe and into a drill-tube, later copied in copper and bronze.

The tools and procedures used for shaping and hollowing stone vessels.

The cutting rates and high losses of metal worn off copper and bronze drill-tubes and saws, employing sand abrasive, for drilling and sawing hard and soft stones.

The use of waste sand/stone/copper particle powders, obtained from drilling and sawing stones, for making faience, for polishing stone and for drilling stone beads.

The indications of serious lung disease caused to workers engaged in drilling and sawing stone with sand abrasive, particularly for making stone vessels.

The indicated ancient employment of stone blocks' surface accuracy testing tools, and of sliding phenomena with regard to lubricated ramps and stone blocks' prepared horizontal and vertical jointing surfaces.

Reusable pottery moulds for mass-producing identical metal castings, and faience artefacts.

Clusters of furnaces, enabling casting of large copper and bronze tools and of artefacts.

The interchangeable tool drill-stock.

The construction and use of three calibrated replica surface testing tools for accurately fitting stone blocks together in the Great Pyramid.

Expendable flint tools for cutting soft and hard stones to shape, and for incising hieroglyphs into them.

The quick-release, adjustable counterweighted tourniquet lever.

The adjustable tripod anvil for beating metal vessels to shape, and for exterior finishing procedures for stone vessels.

The functions of the New Kingdom yarn twisting tool.

The adaptation of tree branches to make bow-shafts, Y-shaped woodworking supports, tripod anvils and stone vessel manufacturing tools' main shafts, and lashed-on forked shafts for driving stone borers.

The recorded experimental cutting capabilities of single copper and bronze bead drills, in addition to establishing the functions of the New Kingdom simultaneously operated mass-production bead-drilling equipment.

The establishment of New Kingdom workshop mass-production methods.

University of Manchester

Higher Doctorate Candidate Declaration

Candidate name: Denys Allen Stocks

Faculty: Humanities

Higher Doctorate Title: Doctor of Letters

Declaration to be completed by the candidate:

1. All of the research and experiments, including all manufactured tools and artefact tests, and their evaluation and results contained within each of the twenty-two publications presented in support of this Higher Doctorate, are contributed solely by me, Denys Allen Stocks. There are no co-authors or collaborators for any part of my work.

2. None of the work presented has been submitted in support of a successful or pending application for any other degree or qualification of this or any other University or of any professional or learned body.

I confirm that this is a true statement and that, subject to any comments above, the submission is my own original work.

Signed: D. A. Stocks **Date:** 14th October 2018

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Statement

A. Degree, other qualifications, research experience and eligibility

Degree qualification:

Degree of Master of Philosophy (1986-8), Department of Archaeology, Faculty of Arts, University of Manchester. (Thesis 13543: two volumes).

Other qualifications:

1. Postgraduate Certificate in Education (1988-9) in Design and Technology, and History, Department of Education, University of Manchester.
2. Certificate in Egyptology (1980-3), awarded with distinction, Department of Extra-Mural Studies, University of Manchester. (Dissertation: one volume).

Research experience:

In preparation for the establishment of an experimental ancient Egyptian technology research project, in 1969, I had privately studied general aspects of Egyptian archaeology. During this extended learning process I began to focus my attention upon areas of technology where archaeologists' awareness of technical matters lacked detailed knowledge. For example, and there are many, how, and with what tools, did craftworkers manufacture artefacts of soft and hard stones, and how did they accurately fit stone blocks together for buildings?

Between 1986-8, the late Professor Barri Jones kindly instructed me, as one of my Master of Philosophy supervisors, in the principles of field archaeology, and in July 1987 supervised me in practical field archaeology at a suspected Roman military camp at Cawdor, Scotland, UK.

Eligibility under the University of Manchester's Ordinances and Regulations for Higher Doctorates:

I am a graduate, other than honorary, of the University of Manchester of thirty years' standing from award of the degree of Master of Philosophy in July 1988.

B. Complete and numbered list of the publications submitted (grouped chronologically):

1 1989a. 'Ancient factory mass-production techniques: indications of large-scale stone bead manufacture during the Egyptian New Kingdom Period', *Antiquity* 63: 526-31.

2 1989b. 'Indications of ancient Egyptian industrial interdependence: preliminary statement', *The Manchester Archaeological Bulletin* 4: 21-6.

3 1993a. 'Making stone vessels in ancient Mesopotamia and Egypt', *Antiquity* 67: 596-603.

4 1993b. 'Technology and the reed', *The Manchester Archaeological Bulletin* 8: 58-68.

5 1997. 'Derivation of ancient Egyptian faience core and glaze materials', *Antiquity* 71: 179-82.

6 1999a. 'Stone vessels and bead making', in K.A. Bard (ed.), *Encyclopedia of the Archaeology of Ancient Egypt,* 749-51. London and New York: Routledge.

7 1999b. 'Stone sarcophagus manufacture in ancient Egypt', *Antiquity* 73: 918-22.

8 2001a. 'Leather', in D.B. Redford (ed.), *The Oxford Encyclopedia of Ancient Egypt*, vol. 2, 282-4. New York (NY): Oxford University Press.

9 2001b. 'Stoneworking', in D.B. Redford (ed.), *The Oxford Encyclopedia of Ancient Egypt*, vol. 3, 324-7. New York (NY): Oxford University Press.

10 2001c. 'Tools', in D.B. Redford (ed.), *The Oxford Encyclopedia of Ancient Egypt*, vol. 3, 442-5. New York (NY): Oxford University Press.

11 2001d. 'Testing ancient Egyptian granite-working methods in Aswan, Upper Egypt', *Antiquity* 75: 89-94.

12 2001e. 'Roman stoneworking methods in the eastern desert of Egypt', in N.J. Higham (ed.), *Archaeology of the Roman Empire: A Tribute to the Life and Works of Professor Barri Jones*, 283-6. Oxford: Archaeopress. BAR International Series 940.

13 2002. 'Technical and material interrelationships: implications for social change in ancient Egypt', in W. Wendrich and G. van der Kooij (eds.), *Moving Matters: Ethnoarchaeology in the Near East. Proceedings of the International Seminar held at Cairo, 7-10 December 1998*, 107-16. Leiden: Research School of

Asian, African, and Amerindian Studies (CNWS), Universiteit Leiden, The Netherlands.

14 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.
Note: my book has been cited 87 times in the Google Scholar web search engine, scholar.google.com (October 2018).

15 2003b. 'Immutable laws of friction: preparing and fitting stone blocks into the Great Pyramid of Giza', *Antiquity* 77: 572-8.

16 2005. 'Auf den Spuren von Cheops' Handwerkern', *Sokar* 10 (1/2005): 4-9.

17 2007. 'Werkzeugkonstrukteure im Alten Ägypten', *Sokar* 15 (2/2007): 74-81.

18 2009. 'Das Bewegen schwerer Steinobjekte im Alten Ägypten: Experimente in der Ebene und auf geneigten Flächen', *Sokar* 18 (1/2009): 38-43.

19 2013. 'Stoneworking, Pharaonic Egypt', *Encyclopedia of Ancient History*, vol. 11, 6407-12. Oxford and New York: Blackwell Publishing Ltd.

20 2015. 'Some experiments in ancient Egyptian stone technology', in C. Graves-Brown (ed.), *Swansea Conference - Experiment and Experience: Ancient Egypt in the Present*, 173-99. Swansea: Classical Press of Wales.

21 2016. 'Scientific evaluation of experiments in Egyptian archaeology', in Campbell Price, *et al* (eds.), *Mummies, Magic and Medicine in Ancient Egypt: Multidisciplinary Essays for Rosalie David*, 446-60. Manchester: Manchester University Press.

22 2018. 'The Materials, Tools, and Work of Carving and Painting', in V. Davies and D. Laboury (eds.), *The Oxford Handbook of Egyptian Epigraphy and Palaeography*, Oxford: Oxford University Press. Forthcoming.
Note: my peer reviewed, commissioned contribution to this volume has been accepted by the publisher.

Preface and Acknowledgements

Between 1999 and 2010 over one hundred replica and reconstructed ancient Egyptian tools were transported to Egypt, being rigorously further tested, and analysed, under local conditions at sites relevant to the tools' ancient uses. For example, the surfaces of some blocks in the Great Pyramid at Giza, and the top surface of the Unfinished Obelisk at Aswan, were tested for accuracy with calibrated replica tools: other experiments at Luxor investigated the fitting of stone column segments in Karnak Temple, using experimentally manufactured stone segments. I wish sincerely to thank the Egyptian Supreme Council for Antiquities (SCA) for their numerous kind permissions, under local Inspectors' supervision, to carry out experiments and critical measurements at various sites in Egypt.

In addition to evaluating these tools' performances in Egypt, and their connected processes, together with some suggested interrelationships with other tools, or with groups of tools, in order to focus upon ancient Egyptian social evolution, I have endeavoured to present the introduction of invented ancient tools and processes in a chronological manner, according to the available evidence. Similarly, my submitted twenty-two published works are chronologically arranged at the end of the overall summary, in order to illustrate the continuous development of the research project.

Significantly, initial investigations with a number of ancient Egyptian tools and processes appeared to show that they were linked to other tools and processes. Consequently, the experiments sometimes revealed difficulties in satisfactorily investigating one tool in isolation, it invariably possessing a probable interrelationship with another tool, or group of tools, all used to create a single artefact.

The thesis is accompanied by a DVD entitled, *Online Egyptology: a day with Denys Stocks. The tools and the technology of Ancient Egypt*. Filming took place in the Manchester Museum on 11 March 2013: Kate Hilton edited it into seven parts, the sound being provided by Jamie Weston. Dr. Joyce Tyldesley, Senior Fellow, Higher Education Academy, University of Manchester and Dr. Campbell Price, Curator of Egypt and the Sudan, Manchester Museum, University of Manchester supported and assisted me with the film's presentation: extracts from the film form part of the University of Manchester's Distance Learning Courses in Egyptology. I very much thank Drs. Tyldesley and Price for their kind permission to use this film in support of my thesis.

C. Overall summary of the aims and achievement of the work:

Chapter 1

Introduction:[1] towards an understanding of the development of ancient Egyptian technology and innovation through experiments

The following chapters, 1-16, demonstrate why I am able to achieve a Higher Doctorate. I believe that I have satisfied the criteria for a Higher Doctorate by putting forward a mix of evidence to support my Higher Doctorate thesis contents. Essentially, I have, firstly, conducted comprehensive research into ancient Egyptian technology through a variety of ways. For example, the archaeological evidence, the pictorial evidence, including written material accompanying tomb illustrations, and in other places, such as on temple walls, are detailed below in this chapter.

Secondly, I have used my mechanical engineering training to manufacture replica and reconstructed tools for experimental test, analysis and evaluation, and then to show how these experimental tools and their associated processes developed Egypt's economy and, therefore, its social evolution.

In each chapter a sub-topic is explained and summarized, the research experiments leading to some major discoveries. For example, Chapter 3 summarizes my discovery of a previously unknown raw, waste, sand-based powder, contaminated with copper particles worn off copper tubular drills and saws by sand abrasive, these two tools being employed to make large artefacts in different hardnesses of stone, such as travertine and granite. Chapter 5's experiments show how the travertine and granite powders formed the basis for faience cores and glazes respectively, as well as for other purposes that are explained in Chapter 5.

My experimental research project is unusual, as it includes public outreach components, such as television, radio, newspapers, lectures, and teaching public courses at the University of Manchester to disseminate the work and its research results.

My publication output is academic, whilst at the same time involving manufacturing, testing, analyses and evaluations of the experimental tools and processes. In other words, the research is 'dual-purpose' but, nevertheless, has impacted on public knowledge of science, technology and the inevitable changes to the social evolution of a technological society, when or wherever it happens.

Aims of the research project

The aims of my project research are to investigate, through experimental manufacture, test, analysis and evaluation, how replica and reconstructed tools, and their indicated associated techniques and processes functioned, in order to establish how ancient tools, techniques and processes operated, together with suggested consequences to the Egyptian economy, to its organization and to its effects on social evolution, a watchful eye being kept upon any interrelationships between groups of tools and processes.

Some observations on the reconstruction of crucially important ancient tools

Studying textual and archaeological evidence has contributed to our knowledge of ancient Egyptian technology. However, it is clear that a number of vitally important tools have not been discovered: it is unlikely that certain copper and bronze tools can ever be found, due to ancient craftworkers conservatively recycling copper and bronze from worn down tools to cast new, replacement ones. Crucial industries, for example the tubular drilling and sawing of hard stones, like granite, and the hollowing out of large numbers of both hard and soft stone vessels, depended upon an uninterrupted supply of specialist tools and trained artisans.

Fortunately, numerous tomb illustrations of tools and techniques, some with texts incorporated into them, have assisted the research. And, also, marks left upon artefacts and upon ancient monuments up and down Egypt, for example horizontal striations visible in saw-slots, and striated circular holes, which still retain broken-off core-stumps within them. These marks, and others, tantalizingly indicate the existence of tools and techniques connected to little-known industrial processes: without the tools that caused such marks considerable gaps exist in our knowledge of the capability of ancient craftworkers to manufacture stone vessels, sarcophagi, sculptures, and other diverse objects excavated by field archaeologists.

It could be expected that changes to tools and processes gradually occurred over time, but where some tools' designs could not be bettered then these tools would be used by generation after generation of ancient craftworkers. For example, the stone-working, wide-edged *copper* chisel did not change in form throughout ancient Egyptian civilization. The wide-edged, flat copper chisel, and the crosscut, narrow-edged copper chisel designs, are still in use today, but are now made from specialized chisel steel. However, later in ancient Egypt's history the casting of harder chisels in *bronze* dramatically improved chisels' cutting capabilities and speeds, also increasing the interval between edge-sharpening.[2]

Establishing an experimental project

In order to investigate how ancient Egyptian technology evolved through the millennia, I decided, in 1969, to establish an experimental archaeology project with the capability to create any type of tool, or other artefact: these efforts were assisted by my mechanical engineering technical apprenticeship, and later as a High School teacher of Design and Technology, and of History at Manchester High School for Girls, UK.

All of the replica and reconstructed tools were, at first, experimentally tested and evaluated in my home workshop in Manchester, UK, but later under realistic situations in Egypt, some even in a granite quarry at Aswan and in a limestone quarry at Tura, and also at monuments with permission of the SCA in Cairo. Indicated techniques and processes for both replica and reconstructed tools were carefully analysed and evaluated, singly at first, but later, with particular groups of tools, to verify suggested technological interrelationships.

From the outset, my project manufacturing operations would be guided by the following methodology and principles:

1. That the replica and reconstructed tools, and any other artefact, would be made according to the strictest evidence for the tools and other artefacts, the materials employed being as similar as possible to those used in ancient times. Where slight doubt or uncertainty arose, particularly where a logical progression or an outcome might be accepted as *de facto*, a note of caution would be raised in the work's written records, and in any publication containing project experiments.

2. To study archaeological publications, taking note of the considered opinions of archaeologists and epigraphists excavating and copying texts at sites up and down Egypt.

3. To view in museum collections around the world, and especially in Egypt, and to examine by touch, wherever possible, tools and artefacts made from various materials, including stone, copper, bronze, iron, wood, as well as artefacts constructed from natural materials, such as types of flora. Other materials derived from animals, for example leather, ivory and bone, were also examined. Artefacts and tools made in all periods of ancient Egypt were scrutinized, commencing at

the beginning of the Predynastic Period, following on into the Dynastic Period until the end of Egyptian civilization.

4. To examine the evidence of ancient technology through the careful and considered study and interpretation of illustrations of manufacturing processes, tools and techniques displayed in tomb scenes, and on other materials, such as papyrus, pottery and limestone ostraca.

5. To construct a casting furnace of similar dimensions to examples displayed in tomb illustrations.[3] The project furnace was designed to be dismantled and rebuilt for the next convenient casting operation, being used eight times to achieve all of the castings needed for manufacturing replica tools, and all revealed reconstructed tools requiring copper and bronze parts. The furnace's construction employed recycled materials.

6. All materials employed to manufacture the replica and reconstructed tools came from the local environment, without inflicting unnecessary damage to it. For example, tools requiring wood for handles, and for other purposes, utilized necessarily pruned tree branches, later fully seasoned, which could be cut and carved with serrated copper saws and knapped flint tools. In this way, all handles became fitted to the correct replica and reconstructed tools. Only then could the ancient effort surrounding the design and making of tools, as well as to manufacture large and small artefacts, and to raise large stone buildings, be appreciated.

Much later in the project the opportunity arose to use a scanning electron microscope (SEM), and other laboratory apparatus, which permitted the scientific examination of certain materials produced as a result of the experiments. In particular, SEM micrographs of project-produced sand-based powders, a waste product of drilling and sawing various hard and soft stones with copper tubes and saws with sand abrasive, were useful in understanding these processes. This waste product will be examined in Chapter 5.

Some project manufacturing procedures

Critical analyses of a large cross-section of illustrations, and marks of numerous types, have informed the research project's experimental reconstruction of tools missing from the archaeological record: my engineering training in industrial tool-making assisted in the interpretation of the ancient illustrations and tool marks with regard to manufacturing ancient tools.

All constructed project tools, including the furnace and test artefacts, *only* employed rudimentary hand methods. The furnace permitted the casting of fifty-one tools, and other artefacts.

Briefly, but not exhaustively for this overall summary, my project tools consisted of twenty-five cast and cold-hammered copper and bronze chisels, the thirteen bronze chisels in this group containing tin percentages ranging from 1% tin up to 15% tin, in order to identify the copper/tin alloy giving the hardest edge after cold-hammering a chisel's taper to shape; adzes and axes, similarly cold-hammered to shape; flint and chert chisels, punches and scrapers; wood-cutting drills, saws and chisels; a fire-stick and its bow; small and large tool-driving bows; jewellers' drills; leather-working awls and augers; vase hollowing tools (and a limestone vase made with these tools); copper and bronze stone-cutting tubular drills and stone-cutting saws; copper and bronze borers; three replica Dynastic copper needles and a replica copper Predynastic pin,[4] and many tools made solely from wood or from rope and/or string, for example mallets, stone blocks' surface accuracy and orientation testing tools, a yarn twisting tool, a tripod anvil and a counterweighted tourniquet wooden lever.

I believe that such a large group of full-sized replica and reconstructed tools and artefacts has never before been manufactured in similar ancient materials for test, analysis and evaluation.

Natural phenomena and mechanical principles (1)

An important area of interest connected with my experimental project's research is whether an established relationship ever existed between science and technology in ancient Egypt. Specifically, did any craftworker or person in authority over craftworkers need to possess any *real* understanding of scientific laws in order to design and make tools?

A scientific law, or a natural phenomenon, and a mechanical principle incorporated within a tool for operating it, are subject areas examined in the Discussion and Conclusions (Chapter 14) of this overall summary, where the findings of some experimentally manufactured replica and reconstructed tools' uses revealed certain natural phenomena and mechanical principles built into them, making it probable that ancient tools' designs, construction and uses were also associated with similar natural phenomena and mechanical principles.[5]

In this thesis, after most chapters, the terms *natural phenomena* and *mechanical principles*, rather than the words, *science* or *scientific laws*, unless they refer to modern scientific investigative techniques, are employed to illuminate a specific tool's design and its work performance.

The test results of all tools manufactured and utilized for this project indicate, to some degree, how the economy of ancient Egypt gained from the intermittent introduction of highly important tools, technical procedures and materials, and how suggested interrelationships and interdependence between some tools' designs and technologies, and their further development, gave impetus to the expansion of ancient Egypt's industrial capability.

The Discussion and Conclusions chapter additionally explores the effects of increased economic activity upon organizational changes operating within a more vigorous economy which, in turn must, in part, have influenced the rapidity and nature of social evolution in ancient Egypt.

Short findings sentences will close each chapter, informing the Discussion and Conclusions chapter. Additionally, where the experiments indicate a natural phenomenon, and/or a mechanical principle assisting a tool's operation, in a majority of chapters, these briefly are recorded under appropriate headings immediately following the findings heading.

In Chapters 2-13 the problems requiring resolution are stated at the commencement of all twelve chapters. I indicate the *Research impact* of the publications at the ends of these chapters, including citations and reviews. My contribution to experimental archaeology is placed at the end of Chapter 16.

Footnotes:

1. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 1-3.
2. Ibid., 56-65, tables 2.1, 2.4, figs. 2.50-2.55.
3. Ibid., 39-40, fig. 2.23.
4. Petrie, W.M.F. 1917. *Tools and Weapons*, London: British School of Archaeology in Egypt, pl. LXV, N109; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 47-50, figs. 2.34, 2.36-2.38.
5. Stocks, D.A. 2007. 'Werkzeugkonstrukteure im Alten Ägypten', *Sokar* 15 (2/2007): 74.

Chapter 2

The cutting of stone, wood and other materials

The problem requiring resolution

How did craftworkers cut stone and other materials in ancient Egypt? Although some limited experiments have been carried out by archaeologists,[1] it is clear that experiments involving comprehensive hardness testing of replica copper, bronze and iron chisels, together with accompanying experiments with stone tools, are required to provide a more coherent picture of sharp-edged tool use.

Copper and bronze tools for cutting soft stones, and wood: hardness comparisons vis-à-vis material cutting capability

The introduction of smelted and cast copper at the commencement of the Nagada II period (c. 3600 BCE) enabled craftworkers to imitate the shapes of certain stone tools in copper, first mentioned by Sir Flinders Petrie in 1917.[2] In the Predynastic Period there existed *four* stone tools for working a variety of natural materials, including wood and stone. These tools were the flint (hardness Mohs 7) end-scraper, the denticulated flint sickle, the flint knife and the stone hand-axe. It is likely that these fundamental design shapes of flint tools' cutting edges were *copied* in copper, making *five* tools, namely, the chisel, the adze, the saw, the knife and the hafted axe.[3]

The initial research part of the experimental project, which concerned tools for cutting stone of most types employed for artefacts, and for buildings, in ancient Egypt immediately pointed towards a fundamental problem relating to the working of the so-called *soft* and *hard* stones. But trying, imprecisely, to define what a 'soft' stone is, relative to a 'hard' stone, and without any explanatory technological information to assist with the tools and methods for cutting any 'soft' and 'hard' stones, has no real meaning when talking about tools and techniques underpinning important ancient Egyptian work practices.

However, by employing a recognized and universally accepted engineering hardness value for all project manufactured and investigated replica copper and bronze chisels, having been cast, and later beaten to shape in metals containing similar scientifically established constituents for ancient copper and bronze chisels,[4] and then individually related to my cutting tests on all main stones between the geological hardness scale Mohs 2 (gypsum) and Mohs 7 (granite), for each replica tool, revealed an improved way of defining what 'soft' and 'hard' stones really are. In this manner, a more realistic definition of both 'soft' and 'hard' stones could be created, with a recognized demarcation line separating the 'softer' stones that effectively could be cut, in ancient times, with copper and bronze chisels, and the 'harder' stones that could *only* be cut with stone tools.

In order for me to determine each copper and bronze chisel's hardness, testing was carried out on its hammered taper using a Vickers Pyramid Hardness testing machine: hardness is established by the use of an inverted, pyramid-shaped diamond indenter placed under a known load for a fixed time. Six indentations are made into a chisel's taper. The Vickers Pyramid Number (VPN), resulting from a mathematical equation, is an expression of the relationship of a known force upon a known area, and a higher number indicates a greater hardness of the metallic tool under investigation. The average of the six values obtained from the six indentations gives the final VPN. The hardest *copper* chisel tested, after hammering (VPN 181), showed that its taper nearly equals the hardness of modern cold rolled mild steel (VPN 192), while the hardest *bronze* chisel's taper, after hammering (VPN 247), exceeded the hardness of unworked chisel steel of VPN 235. (But note: VPN 800 is obtained after hammering the taper of such a steel chisel, but test cutting of granite revealed that even this modern chisel's hardness is insufficient to cut igneous stone types).

The hardness number for each chisel enabled a hardness relationship between the project chisels to be established, which could then be related to each chisel's cutting characteristics when performing test work on wood and stone.

In this study, and consequential experiments on cutting stone, composition analyses of some *ancient* copper and bronze chisels would provide a guide to *estimated* hardness numbers for them, and that these estimated hardness numbers would indicate likely ancient chisels' capabilities for cutting particular stone types when compared to the cutting tests performed by replica copper and bronze chisels of a broadly similar metallic content.[5]

In September 2004, at Giza, Cairo, Atlantic Productions, London filmed a television documentary, *Secrets of the Sphinx: Revealed*, for Discovery Communications - The Science Channel, and for Channel Five, UK. Part of the film involved the test cutting abilities of two of my experimental replica copper chisels for sculpting a scale representation of the head of the Great Sphinx at Giza into a large Tura quarry limestone cube, the interior of the cube being quite hard compared with the stone surrounding it. Professor Glynn Williams, University

College London, the sculptor, used the copper chisels on the initial roughing-out of the head. The chisels suffered no visible wear to their edges. I was the ancient technology consultant for this documentary.

In December 2005, Atlantic Productions, London made a television documentary in Egypt for the History Channel's *Lost Worlds Series* on the construction of Karnak Temple, including aspects of architecture and engineering. In an Aswan quarry, I demonstrated chiselling and sawing hieroglyphs into a block of red sandstone, and one of limestone, carried out with two experimental replica chisels, one of copper, the other of bronze, a replica copper serrated saw, some flint scrapers, and a reconstructed copper tubular drill, operating on dry sand abrasive, for revealing the ancient technique of delineating a circular hieroglyph for the Sun-God, Rē‘. All of the tools suffered no visible wear. I was the ancient technology consultant for this documentary.

Later evaluation of all of the undertaken stone-cutting experiments suggests that no experimental copper or bronze chisel for this study, nor *any* ancient copper or bronze chisel, could *effectively* cut stone other than gypsum (hardness Mohs 2), red sandstone and soft limestone (both hardness Mohs 2.5), and steatite (hardness Mohs 3). All of the experimental chisels easily cut hard and soft wood types. An experimental serrated copper saw also cut soft limestone and red sandstone,[6] in addition to all woods.

Late Period iron chisels' capabilities for cutting soft and some hard stones: indicated stone tools for cutting moderately hard and igneous stones

My experimental cutting tests with a modern steel chisel (VPN 800) on granite, diorite and porphyry clearly demonstrated that Late Period craftworkers could not possibly have used their much softer iron chisels for cutting hieroglyphs and reliefs into these types of stone. The experimental steel chisel, forged from carbon steel, immediately became blunted, with the outer parts of its edge torn away. There is written evidence, from an ancient source, that Late Period iron chisels could not cut very hard stones.

Theophrastus, a Greek Peripatetic philosopher (c. 372 – 287 BCE), who lived contemporaneously during a part of the ancient Egyptian Late Period, provides a valuable insight as to whether iron or stone tools, at that time, were used for cutting the hard stones. In Books LXXII and LXXV, of *History of Stones*, Theophrastus writes:

> As that some of the Stones before named are of so firm a Texture, that they are not subject to Injuries, and are not to be cut by Instruments of Iron, but only by other stones...and others yet, which may be cut with Iron, but the Instruments must be dull and blunt: which is much as if they were not cut by Iron.[7]

The 'Instruments of Iron' referred to by Theophrastus are likely to be chisels and/or punches. But what are the 'other stones' referred to by Theophrastus?

The iron tools available in Theophrastus' time were inferior in hardness and toughness to the steel tools available to the Roman masons cutting purple porphyry and grey granite at Gebel Dokhan (Mons Porphyrites) and Mons Claudianus respectively in the eastern desert of Egypt during the first to the fourth centuries CE.[8] Hardness tests conducted on a second century CE Roman high carbon steel stonemason's chisel from Chesterholm, UK revealed a variable edge hardness of VPN 579 down to VPN 464.[9] But even these chisels were incapable of cutting grey granite and porphyry without suffering immediate serious damage.

My present experiments indicate that the Roman masons must have used a harder material for their chisels at Mons Porphyrites and at Mons Claudianus, particularly for incising inscriptions, and there is evidence that Roman stone-workers collected grey flint nodules from the Wadi Abu Had situated some fifty kilometres to the north of Gebel Dokhan, which could have supplied knapped flint chisels and punches for working the purple porphyry.[10]

For earlier evidence regarding ancient Egyptian stone-workers' tools and techniques for cutting granite, good examples of cut- and punch-marks on edges of unfinished hieroglyphs can be seen incised into rose granite columns of the Nineteenth Dynasty Temple of Herishef at Heracleapolis.[11]

Project experiments to cut very hard stones utilized in ancient Egypt, particularly granite, porphyry, diorite, basalt and quartzite, with obsidian tools, and other tools made from hard stones, including flint and chert, reveal that only flint chisels and punches can effectively cut granite and other stones of hardness Mohs 7. Experimental flint chisels and punches were able to replicate the cut- and punch-marks seen in the granite columns of the Heracleapolis Temple of Herishef.[12] However, experimental flint tools for cutting hard stone to shape, and incising hieroglyphs into such stone, caused the tools to splinter and shorten over time.

Such tools may be referred to as *expendable* tools, a cost worth paying for flint tools' capabilities for working any stone hardness. The 'other stones' mentioned by Theophrastus are likely to be chisels and punches made from flint.

It is also apparent that other technical practices owed their development to the existence of a hard tool material that could be given exceptionally sharp edges; for example, four copper razors in the British Museum (BM 6079-82) are engraved with the name *Idy*. Experiments with knapped flint tools demonstrated their ability to cut annealed copper sheet, the incisions being similar to the engraved marks on the copper razors.[13]

Research impact

My research in this chapter has, for the first time, shown what types and hardness of all stones were effectively cut by copper, bronze, iron, steel and flint cutting tools. This has had a major impact on archaeology in other parts of the world.

Erhan Tamar cited my experimental working of igneous stones with stone tools, which has assisted his research into whether iron tools or stone tools worked hard stones in the Syro-Anatolian Region in the Iron Age.[14]

Findings: my experiments defined the demarcation line for effectively cutting particular softer stones with copper and bronze chisels to be hardness Mohs 3. Flint was employed for cutting stones of a higher hardness (up to hardness Mohs 7), including travertine (hardness Mohs 3-4). Late Period iron chisels could effectively cut stones up to, and including, hardness Mohs 4-5.[15]

Natural phenomena: none applicable.

Mechanical principles: none applicable.

Footnotes:

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12. Stocks, D.A. 2018. ‘The Materials, Tools, and Work of Carving and Painting’, in V. Davies and D. Laboury (eds.), *The Oxford Handbook of Egyptian Epigraphy and Palaeography*, Oxford: Oxford University Press. Forthcoming.
13. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 95.
14. Tamar, E. 2017. ‘Style, Ethnicity and the Archaeology of the Aramaeans: The Problem of Ethnic Markers in the Art of the Syro-Anatolian Region in the Iron Age’, *Forum Kritische Archaologie* 6 (2017): 38, note 174. Tamar quoted from, Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 63-4, 78.
15. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 64.

Chapter 3

Drilling and sawing hard stone

The problem requiring resolution

Tubular-shaped drill marks and saw slots are to be seen on ancient artefacts, but there are no known drills or saws capable of causing these marks and slots, nor are there any illustrations of the tools and techniques in use by ancient craftworkers to accomplish this work. With what tools and techniques did craftworkers drill and saw stones for making artefacts, such as stone vessels and sarcophagi?

Tubular drills constructed from reeds, copper and bronze

Sometime after the beginning of stone vessel manufacture, and before c. 3600 BCE, when the casting of copper artefacts became established, workers probably employed the common reed, used with a loose abrasive, as a tubular drill for initially hollowing the interiors of stone vessels manufactured from hard limestone and travertine: this technique considerably shortened the time needed to hollow the interiors of stone vessels.[1] It is likely that the common reed directly served as a pattern for Nagada II Period (c. 3600-3200 BCE) copper copies, which were able to drill into much harder stones than reed tubes.

The Egyptian coppersmith knew how to make tubes of copper during the Nagada II Period, which is confirmed by a copper tubular bead, now in the Petrie Collection, University College London (UC 5066), from a grave at Nagada:[2] tubular slots in various stone artefacts of Dynastic date were made with copper tubular drills,[3] which enabled the rapid increase in the manufacture of hard and soft stone vessels.

My test drilling with the bow-driven reed tubes necessarily used dry sand abrasive, as wet sand collapsed the tube in upon itself. The reeds proved their ability to cut hard limestone, slate and travertine: the cutting rates improved for soft limestone, red sandstone, gypsum and steatite.[4] Experimental, reconstructed copper tubes determined their ability to drill into granite, porphyry, basalt and diorite, utilizing dry sand abrasive, which flows just like a fluid does: but test drilling with wet sand proved to be counterproductive, as wet, used up powdered sand could not be withdrawn from deep holes, whereas dry powders packed into the inside of the tube and could be withdrawn and replaced with raw, unused sand.[5]

Small-scale experimental tests in my UK workshop established the initial sawing and drilling data – the volumes of ground away copper particles and the volumes of stone sawn and drilled out[6] - but in March 1999 an opportunity arose for me to carry out large-scale experiments to saw and to drill rose granite in a quarry located on the edge of the southern Egyptian town of Aswan. Quarry workers, trained by me, operated a 1.8 m-long flat-edged copper saw (two sawyers)[7] and an 8 cm-diameter, flat-ended copper drill-tube (three drillers).[8]

My 1.8 m-long reconstructed saw blade, stood on its edge, measured 15 cm in depth, 6 mm in thickness and weighed 14.5 kg, the saw's flat edge acting on dry sand abrasive: the granite block to be cut measured 95 cm in width. Two workers pushed and pulled this stone-weighted saw from opposite sides of the block. Parallel striations of varying lengths, depths and widths, similar to those seen in ancient sawn stone objects, were visible on the sides and on the bottom of the slot, and upon the saw's edge. The rate of cutting amounted to 12 cm^3/hour:[9] the used *dry* sand powder, light grey in colour, poured over each end of the slot, its copper particle content intact.

The experimental tubular drilling of a rose granite block required the assembly of the component parts of my reconstructed drilling equipment: the 8 cm-diameter copper tube, the wooden drill-shaft partly force-fitted into it, the driving bow and rope, and a capstone bearing in which to rotate the upper end of the drill-shaft upon dry sand abrasive. I chipped a groove by flint chisels and punches into the granite's surface, which allowed the tube to be located for rotation with the bow, clockwise and then anticlockwise.

The gyratory actions of the rotating drill-tube's exterior wall ground the hole's circumference into a taper which sloped inward to its bottom, and the tube's interior wall ground the core into a reversed taper, i.e., narrower at the top and wider at the bottom. The tubular slot, importantly, also became tapered.

I broke the core away at its base by soundly hammering two adjacently placed tapered flat chisels inserted vertically into the tapered slot: the stone hammer blows forced the core over, causing the brittle granite to be placed under such tension that it parted completely, allowing the core to be extracted in a single piece.[10] The tubular drill's cutting rate amounted to 5.2 cm^3/hour.[11]

No full-sized experimental tubular drilling and sawing of granite has ever been undertaken in an Aswan rose granite quarry, the only place in Egypt where ancient workers obtained such stone for manufacturing sarcophagi and other artefacts.

The March 1999 sawing and drilling of granite experiments, together with the core's removal technique, were filmed by NOVA/WGBH Boston, United States for a television documentary, *Ancient Technology: Obelisk II*, later transmitted on PBS America Channel in the United States, and on Channel 4, UK as *Pharaoh's Obelisk, Mysteries of Lost Empires*. I was the ancient technology consultant for this documentary.

My experiments permitted comparisons to be made with the hollowing of Khufu's Fourth Dynasty rose granite sarcophagus, already sawn to shape, by the employment of a six royal finger-diameter (11 cm) copper tubular drill, the size obtained by using dimensions obtained from Flinders Petrie's measurement of a curved drill-tube mark still to be seen in the eastern internal wall of the sarcophagus.[12]

In February 2005 the SCA kindly permitted me to measure the distance from the vertical centre line of the curved drill-tube mark to the inside of the northern wall: this dimension determined that the curved mark is the fourth drill-hole from the northern wall in a series of eighteen touching holes for the eastern internal side of the sarcophagus, and similarly for the western side. Four holes at each end completed a total number of forty-four holes around the internal perimeter. Their cores were removed, followed by the necessary drilling of a series of spaced-out weakening holes in the middle of the isolated stone mass.[13]

My calculations using the Aswan experimental sawing and tubular drilling data-sets suggest that approximately *half a tonne* of copper was ground off the two tools, thirty-seven tonnes of sand abrasive being turned into a fine powder contaminated with copper particles, created as a consequence of the sawing and drilling operations for Khufu's sarcophagus. The time required for these procedures is calculated to be about two years.

The Aswan experiments, and calculations using the drilling and sawing data-sets, indicate that immense amounts of copper, the loss of many thousands of tonnes over millennia, were ground off stone-cutting drill-tubes and saws.[14] Evidence in support of these experimental results was acquired by Flinders Petrie, who measured a slag heap, the product of copper smelting operations at Wadi Nasb, Sinai: he found that the heap weighed about 100,000 tonnes,[15] and this has been confirmed by A. Lucas.[16] T.A. Rickard calculated that the slag heap resulted from the smelting of about 5,500 tonnes of copper.[17]

The experimentally obtained data-sets, combined with the measurements made by Petrie, Lucas and Rickard, support a conviction that hard stone drilling and sawing operations used up a huge proportion of Egypt's total copper production, the ground-away metal particles inextricably mixing with the powdered sand abrasive whilst making huge numbers of large and small, hard stone artefacts. The consequences of this extraordinarily large copper consumption will be examined in the Discussion and Conclusions chapter.

The techniques used in this chapter can be seen in the accompanying DVD, Part 1: Nature's Designs, Drilling & Sawing, Copper.

Research impact

My research in this chapter has, for the first time, shown how the drilling and sawing of stones of all hardnesses, with copper tubes and saws using sand abrasive, was accomplished in ancient Egypt. My experiments also revealed, for the first time, the production of enormous volumes of a powdered sand/stone material contaminated by particles of copper worn of the drill-tubes and saws. This important discovery has had a major impact on the field of archaeology in other parts of the world.

M.J. & D.E. Fisher cited the large-scale experimental drilling and sawing of granite blocks at Aswan in 1999, which they witnessed as part of the team reporting the separate research discoveries made in the granite quarry and surrounding area in March 1999.[18] Nacho Ares reviewed experimental tubular drilling techniques, which applied to different areas of ancient Egyptian technology, such as the hollowing of stone vessels and sarcohagi.[19]

Robert Partridge reviewed stone-working technology in a general way, mentioning applications of the research for particular ancient Egyptian monuments, and other artefacts of interest to his readership, such as jewellery products and stone vessel manufacturing details.[20] Carolyn Graves-Brown cited experimental stone-working and drilling technologies in support of her explanation of matters experiential and experimental, which appeared in her 'Introduction' to the accompanying book to the *Swansea Conference - Experiment and Experience: Ancient Egypt in the Present.*[21] Elizabeth Healey, for her study of an obsidian bowl from *Alalakh*, acknowledged my assistance by saying, 'Denys Stocks made useful comments on the bowl AT/48/99 from *Alalakh* and gave valuable advice on the use of tubular drills more generally'. [22]

Diane Johnson and Joyce Tyldesley acknowledged my advice on ancient technical aspects of bead production for replicating a small tubular-shaped bead (Manchester Museum, MM 5303) made from a small sample of meteorite iron.[23]

Findings: my drilling and sawing experimental data-sets, obtained in full-scale drilling and sawing of rose granite at Aswan with copper drill-tubes and saws, revealed the exceptionally large consumption of copper and sand utilized to shape and hollow Khufu's rose granite sarcophagus.

Natural phenomena: friction; tension in bow-shaft, string or rope.

Mechanical principles: reciprocating and rotary motions; grinding surfaces with sand crystals by flat-ended copper tubes and flat-edged copper saws; lubrication.

Footnotes:

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5. Ibid., 123-4.
6. Ibid., 115, table 4.2.
7. Ibid., 129-35, figs. 4.19, 4.21.
8. Ibid., 129-35, figs. 4.20-4.22.
9. Ibid., 115, table 4.3A.
10. Ibid., 133-5, figs. 4.23-4.26.
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13. Stocks, Ibid., 920-1, fig. 2.
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21. Graves-Brown, C. 2015. 'Introduction', in C. Graves-Brown (ed.), *Swansea Conference - Experiment and Experience: Ancient Egypt in the Present*, Swansea: Classical Press of Wales, xii, xv, xxiii, xxiv. Publications cited by Graves-Brown included, Stocks, D.A. 2015. 'Some experiments in ancient Egyptian stone technology', in C. Graves-Brown (ed.), *Swansea Conference – Experiment and Experience: Ancient Egypt in the Present*, Swansea: Classical Press of Wales, 174-95.
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Chapter 4

Stone vessel manufacturing capability

The problem requiring resolution

Stone vessel manufacture occupied a position of great importance to ancient Egyptians. There are tomb illustrations of stone vessel making, but hardly any of the tools have been located by archaeologists. How were hard and soft stone vessels manufactured, and with what tools?

Predynastic evidence for stone vessel making

The technology for hollowing stone vessels became established in the Predynastic Period. During the Badarian and Nagada I Periods[1] hard stone vessels were necessarily, and laboriously, hollowed with hand-held stone borers, used in conjunction with desert sand abrasive. The experimental working of hard stone (Chapter 2) indicates that the exterior shaping of all hard stone vessels, even the travertine ones, in every period, must have been completed with flint chisels, punches, scrapers, and sandstone grinders.

In the Nagada II Period, a popular stone vase shape included the oblate spheroid, carved with a rim and two perforated tubular-shaped lugs: a fine example in the Manchester Museum (MM 1776) is made from porphyry.[2] Taller, bulbous lugged jars were made of porphyry, diorite, breccia, serpentine, travertine and limestone.

Some stone vessels in our possession are cylindrically shaped, only requiring a tubular drill for hollowing. Many vessels, though, are bulbous in form: each vessel of this configuration needed widening below the shoulders using boring processes quite separate from the drilling of the interior with a tube. A previously made tubular hole, after core extraction, could be enlarged with successively longer figure-of-eight shaped stone borers, until eventually forming the correct internal shape. The figure-of-eight shaped borer has been discovered at Hierakonpolis, a site associated with Late Predynastic and Early Dynastic stone vessel production.[3]

Some tomb evidence for a stone vessel manufacturing tool

Neither the forked wooden shafts, nor the tools that drove them, have been discovered. However, the tool is depicted as a hieroglyph, the first known one occurring in the Third Dynasty at Saqqara.[4] Different forms of the main tool are illustrated in a number of Egyptian tombs constructed between the Fifth and the Twenty-sixth Dynasties.[5] An excellent, explanatory representation of the stone vessel drilling and boring tool's configuration, where the borer-holding forked shaft is depicted secured by a thin rope to the main shaft, can be seen in a painted Twelfth Dynasty tomb representation displayed in the Fitzwilliam Museum, Cambridge (E55.1914), a limestone fragment from Lahun.[6]

The figure-of-eight shaped borer enabled a forked shaft to engage with the waist, the main drilling shaft being fitted with a copper or bronze tubular drill at the lower end, and also supplied with two weights, or a later, single weight, which always remained fastened in position immediately under an inclined, upper handle. Generally, the main wooden shaft, looking at its top part, appears to be manufactured from a forked tree branch, one part of the fork being cut away, so forming a slanting handle, enabling a worker continuously, but *partially*, to rotate the main shaft clockwise, and then anticlockwise.

Experiments with reconstructed Twist/Reverse Twist Drills

My experiments with ten reconstructed tools[7] of differing sizes and configurations suggested that an operator twisted the main shaft about 90° clockwise, and then anticlockwise, by wrist actions, both hands firmly gripping the handle and shaft without moving them: the copper tubular drill, force-fitted part-way up the bottom of the main shaft, and operated on dry sand abrasive, cut the stone around its *full* circumference with continuous quarter-clockwise and return anticlockwise twists, now named by me to be the Twist/Reverse Twist Drill (TRTD). The sand became ground down into a powder, being contaminated with copper particles ground off the tubular drill.

My test drilling of an experimental limestone vessel with a tubular drill driven by a bow determined that bow-drilling could easily damage a stone vessel with uncontrolled wobbling of the drill-shaft. Supporting this finding there is a parallel-sided core left in an unfinished, uncatalogued stone vessel in the Petrie Collection, University College London, which can only be achieved with a twist/reverse twist action.

One of my reconstructed TRTDs, after successfully testing it for tubular drilling for hollowing a shaped experimental stone vessel, could now be fitted with a forked shaft lashed to the main shaft for twisting a figure-of-eight shaped stone borer. This tool also cut out the stone with dry sand abrasive.[8] With extended use the fork of a reconstructed tool gradually wore down, caused by interaction with the sand abrasive, which prevented the fork from gripping a figure-of-eight shaped borer. However, a forked shaft could simply be replaced by lashing a new one to the main shaft.

The experimental manufacture of my test stone vessel, together with the shaping, drilling and boring of it, is the first such vessel to be made employing indicated reconstructed ancient tools.

The TRTD is an early, prime example of an interchangeable tool system, involving the replaceable lashed-on forked shaft, as well as changing shorter, and longer, figure-of-eight shaped stone borers to achieve the boring of the wider and narrower dimensions of the internal shapes of bulbous vessels, in addition to replacing a worn down copper tube fitted to the main shaft. A main shaft fitted with a tube and weights probably lasted for many years.

The use of the TRTD tool can be seen in the accompanying DVD, Part 2: Twist/Reverse Twist Drill, Flints, Borers.

Research impact

My research in this chapter has, for the first time, shown how the shaping and hollowing of stone vessels made from all stones was accomplished in ancient Egypt. This has had a major impact on the field of archaeology in other parts of the world.

Ian Shaw cited my experimental manufacture of stone vessels when discussing the sequences of a vessel's separate manufacturing operations as parts of a *chaîne opératoire* in a system of vessel creation.[9]

Galal Ali Hassaan cited stone vessel manufacturing tools and techniques as one of the ancient Egyptian ways of cutting stone in a technical appraisal of mechanical engineering in ancient Egypt. Hassaan's inclusion of some of my experimental research on ancient Egyptian technology was explored in his explanations of the subject matter in the *International Journal of Advanced Research in Management, Architecture, Technology and Engineering*.[10] Hassaan drew favourable conclusions on my research methods and results.

Elise Morero cited my experimental manufacturing processes and tools concerning her own research on Mycenaean lapidary craftsmanship enshrined in stone vase manufacture.[11]

Findings: the reconstructed drilling and boring tool's use for making a bulbous stone vessel indicated a high success rate of stone vessel manufacture in ancient times.

Natural phenomena: friction; torque.

Mechanical principles: grinding; interchangeability of parts.

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Chapter 5

Raw materials for manufacturing faience cores and glazes

The problem requiring resolution

Scientific examination of small samples taken from ancient Egyptian faience cores and glazes to determine their contents, and their microstructure, has been unable to pinpoint a common origin of the powders fired into ceramic cores and blue and green glazes. The absence of evidence for the raw materials for making faience has hindered the understanding of the complete manufacturing methods of ancient faience. How did the ancient Egyptians create the raw materials for making ancient faience?

Indicated by-product faience raw materials created by drilling and sawing soft and hard stones

In 1989 I realized that the waste product powders obtained from experimentally drilling and sawing travertine and hard limestone with copper tubes and saws, as well as from drilling and sawing granite and other igneous stones, both tools utilizing desert sand as an abrasive, contained the key constituent components of ancient Egyptian faience cores and blue and green glazes respectively.[1] The powders held, in variable quantities, minute copper particles ground off the drill-tubes and saws, the drilled and sawn stone particles and ground down quartz sand fragments.[2]

The powdered waste product was initially examined and photographed under an SEM. The micrographs depicted shattered, very sharp angular quartz fragments, many occupying the size range of 0.5 – 5 microns: quartz fragments in this size range must have caused serious, progressive lung damage to ancient drillers and sawyers using tools operating on sand abrasive.[3] Most larger angular particles occupied a size range of between 50-200 microns.

After some unsatisfactory experiments, I made a stiff paste from a mixture of 99% of the powder obtained from drilling hard limestone, and, separately, from 99% of the travertine-derived powder, both mixed with 1% $NaHCO_3$ (sodium bicarbonate, a necessary alkaline substance, and obtained as naturally occurring *natron* by ancient faience makers): practically white, friable cores were produced.[4] After drying, firing such cores at a temperature of 850° C, and allowing them to cool without a soak time, created many minute specks of blue randomly scattered in the core material. Using an SEM to analyze the core made from the hard limestone derived powder, '...found it similar to ancient faience in microstructure, especially in quartz angularity and particle size. The bulk composition contained slightly lower silica and higher lime.'[5]

An experimental runny mixture made with 75% granite-derived powder, and mixed with 25% $NaHCO_3$, coated an unfired dried core by direct application. Kiln firing this coated core at 950°C, without a soak time, created a hard, deep blue vitreous glaze.[6]

In October 2004, Edgework Media, Washington, DC made a television documentary, filmed in Egypt, entitled, *What the Ancients Knew* for Discovery Communications – the Science Channel. I was the ancient technology consultant for this documentary. Part of the film's recorded action took place in the Pharaonic Village, Cairo, where the experimental faience manufacture in the UK workshop was repeated by me using waste, copper-contaminated powders created in drilling experiments within the Village's ancient technology exhibition and demonstration area, established by me in 2002. Kiln firing at the Village revealed that a blue glaze, similar to the UK workshop's experimental samples, covered the faience cores.

The experiments powerfully indicate, with other evidence adduced below, that these man-made waste powders obtained from the drilling and sawing of different stone types with copper or bronze tubular drills and saws, utilizing desert sand as an abrasive, are the raw materials for manufacturing ancient faience cores and blue and green glazes; and it could be expected that modern scientific analyses[7] of small samples taken from ancient faience artefacts would all differ in mineralogical and metallurgical content. The varying mineralogical content could be traced to differences in the drilled and sawn stones, and in the sand obtained from different locations: also, the metallurgical content of the coppers and bronzes used to make the tubular drills and saws, whether from newly smelted copper or from metals melted from worn tools, and added to newly smelted metals, would be different for each tube and saw.[8]

However, there is some evidence to indicate a direct connection between the metallurgical and faience industries. J. Riederer's[9] analyses of Late Period bronze artefacts in three regions of Egypt - Lower, Central and Upper – allowed A. Kaczmarczyk and R.E.M. Hedges[10] to compare the average tin concentration in the bronzes with the tin concentration in the faience artefacts found in each region.

The results clearly showed that the tin content of blue and green faience mirrored the composition of contemporary bronzes coming from the same geographical region. This finding supports a proposition that the reason for this correspondence is that the ancient waste powders, containing bronze particles worn off similar tin content in the bronze utilized for manufacturing stone-cutting tubular drills and saws for cutting stones with quartz sand abrasive, were employed for making faience objects in the same geographical region. It is possible, therefore, that a similar correlation could have existed throughout the Dynastic era, and the preceding Nagada II and Nagada III/Dynasty 0 Periods.

My experiments suggest that separate ancient tasks for faience manufacture involved the following operations: the smelting of copper ores; the manufacture of copper tubular drills and saws for drilling and sawing stone artefacts of varying types and hardnesses with dry desert sand abrasive; the transference of waste copper-contaminated/sand/stone powders to nearby faience workshops; the manufacture of faience cores from moist, pliable powders resulting from drilling and sawing hard limestone or travertine; the usual manner of coating air dried cores with a runny powder mixture obtained from drilling and sawing igneous stones, for example granite and basalt, which automatically contained a larger amount of copper particles; firing the ceramics in a kiln at a temperature of about 950°C to make the blue or green glazed faience product.

Other experiments suggest that these finely ground waste materials were also likely to have been used, mixed with water, as a fluid drilling abrasive for perforating hard stone beads with their threading holes, as well as being employed as a stone smoothing and polishing abrasive.[11]

It is improbable that ancient faience manufacturers would have specially made finely ground sand and copper particle powders for faience cores and glazes when huge amounts of similar powders, left as a waste product from the sawing and the drilling of stones, were available. Indeed, the introduction and expansion of modelled faience cores in the Late Predynastic Period, concomitant with the expansion of soft and hard stone vessel manufacture after c. 3600 BCE, supports an idea that faience cores and glazes were regularly manufactured from the waste powders – a *by-product* material - obtained from the drilling and sawing of stones with copper, and later bronze, tubes and saws. In particular, the drilling powders obtained from making stone vessels of various stone types were also available for faience manufacture.

Before my present experiments, no test manufacture of faience cores and glazes for scientific examination have ever been created from waste powders resulting from the drilling and sawing of stone artefacts with copper and bronze tools employing sand as an abrasive.

The foregoing evidence supports the ancient use of waste, copper-contaminated powders for making faience cores and glazes. As a consequence, a considerable proportion of the copper ground off important stone-cutting tools – the tubular drill and saw - could be reused for other, entirely separate industrial, religious and artistic purposes, and not permanently lost at all. It is credible that Predynastic faience manufacturers, employing newly-introduced copper tubular drills with sand abrasive for hollowing stone vessels, comprehended that the waste powders produced could directly be used to make faience cores, blue and green glazes to cover them, in addition to blue frits and pigment.[12]

The discovery of hitherto unknown, tremendously important raw materials for faience manufacture, and for their employment as a fluid drilling abrasive for perforating hard stone beads, as well as its use for a stone smoothing and polishing abrasive, only came about as a result of my original experimental drilling and sawing of different stones with copper tools and sand abrasive. These two raw materials – sand and copper - together with the processes of drilling and sawing a variety of stones formed the backbone of Egypt's industrial economy for the majority of ancient Egyptian civilization.

Research impact

My research in this chapter has, for the first time, shown how the raw, copper-contaminated powdered material left after the drilling and sawing of stone artefacts with desert sand abrasive, was the basis for manufacturing ancient Egyptian faience cores and glazes, in addition to the making of blue frits and pigment. The abrasive powders' other uses were its employment as a fluid drilling abrasive for perforating hard stone beads, as well as for a smoothing and polishing abrasive. I have made a major discovery that has had a major impact on the field of archaeology in other parts of the world.

Two archaeologists working in the field of experimental archaeology, Paul Nicholson,[13] who cited my coating of an unfired dried core by direct application with an experimental runny sand/stone/copper particle mixture before firing it: and Ian Shaw,[14] who cited the relationship between drilling powders obtained from stone vessels being used to make faience, have both demonstrated their support of my experimental work, and its results, flowing from this discovery.

Findings: the experimental faience cores and glazes made from quartz-based drilling and sawing powders, and contaminated with copper particles, are similar in crucial respects to ancient faience. There are strong indications of a by-product powdered material from one industry being used for other, unconnected manufacturing purposes.

Natural phenomena: none applicable.

Mechanical principles: grinding.

Footnotes:

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Chapter 6

Building the Fourth Dynasty Great Pyramid's core- and casing-blocks together

The problem requiring resolution

The joining together, accurately, of approximately two and a half million limestone blocks for constructing the Great Pyramid has puzzled generations of archaeologists. How could masons accurately make flat, horizontal and vertical joints between limestone blocks of considerable weight?

Fitting limestone blocks into the Great Pyramid of Giza

At Giza, in the Fourth Dynasty, Khufu built his Great Pyramid using large limestone core- and casing-blocks for its construction. Khufu's masons not only made each block's top and bottom joint surfaces accurately flat, but they are also parallel to each other and truly horizontal toward the pyramid's central axis and along each of its four sides. Parallelism between every block's top and bottom joint surfaces was essential to guarantee the pyramid's structural stability. How did craftworkers achieve such remarkable accuracy in fitting millions of limestone blocks into Khufu's pyramid? There are several clues helping experimental research into this enigma.

In the early 1880s, Flinders Petrie made careful measurements of the rising joints of several of the remaining large casing-blocks at the base of the northern side of the Great Pyramid. He found that:

> Hence the mean thickness of the joints there is .02 (0.5 mm); and, therefore, the mean variation of the cutting of the stone from a straight line and from a true square, is but 0.01 (0.25 mm) on a length of 75 inches (1.9 m) up the face,...[1]

In 1930, Somers Clarke and Reginald Engelbach also examined casing-blocks.[2] They noticed that the tops of the blocks were dressed *after* they had been laid, and that this procedure sometimes involved part of a core-block lying immediately behind a casing-block. This observation has considerable relevance when contemplating the processes of producing and testing the flatness of both core- and casing-blocks' top surfaces.

In the Eighteenth Dynasty tomb of Rekhmire at Thebes, an illustration[3] depicts the testing of a block's *vertical* surface flatness between cutting and dressing operations, which is achieved by holding two short rods of wood at 90° to the surface, a string being tautly stretched between the tops of the rods. A mason holding a third rod of equal length against the string revealed how much stone needed to be pared away at that point.

A set of three wooden rods has been found at Twelfth Dynasty Kahun by Petrie,[4] now in the Manchester Museum (MM 28), in addition to two model stone block surface orientation frames, one for determining horizontality, and the other for determining verticality, each tool fitted with a plumb line:[5] these two artefacts were both located in the Nineteenth Dynasty tomb of the architect Senedjem at Deir el Medina.

The lengths of the three rods, measured by Petrie, differed in length to each other by not more than the modern dimension of 0.005 cm. My experiments demonstrated that, by using an easily constructed outside calliper, three replica wooden rods could be made closely equal in length, just like the Kahun rods. The replica set of three rods confirmed an ancient capability of making an accurately matched set of three rods: workers were, therefore, capable of preparing large stone surfaces flat to an accuracy of 0.25 mm, confirmed experimentally by me.[6]

Fashioned from three pieces of wood to make an A-shaped frame, for testing horizontal surfaces, the replica frame's plumb line hangs from a hole drilled into the apex: Flinders Petrie found a plumb bob (weight) at the Third Dynasty site of Meidum.[7] In calibrating my replica tool, the frame's two free ends needed just to touch the surface of still water, a vertical mark being made on the horizontal bar exactly behind the hanging plumb line. Reasoning skills are likely to have suggested to ancient craftworkers that still water equated to the flat, horizontal limestone block surface required to build the pyramid, reinforced by knowledge of irrigation techniques that, at times, must have revealed still water's characteristics – a flat horizontal surface in all directions. Further, craftworkers probably reasoned that a plumb line *always* hangs vertically, and at a right-angle, to the flat surface of still water, and at any position through a full circle around it. The craftworker may also have allowed the plumb bob to hang *below* the water's surface, permitting a wooden setsquare accurately to be calibrated against the plumb line.

A replica vertical testing F-shaped frame required the two horizontal pieces to be exactly the same length, using an outside calliper to achieve this requirement *after* firmly fastening them to the vertical length of wood. A hole drilled into the slightly projecting top of the vertical piece, and another hole drilled at an angle of forty-five degrees through the end of the upper horizontal piece, permitted the plumb line to be threaded through the two holes, leaving the line hanging freely against the lower horizontal piece, when truly vertical. Provided each piece of timber is accurately made and fitted together, using an outside calliper for final adjustments, an ancient tool for testing verticality *automatically* became calibrated at the end of the construction process.

Without the set of three rods, together with the A-frame and the F-frame, the building of stable stone temples, pyramids and free-standing walls would have been extremely difficult.

The Great Pyramid's stone blocks' accuracy verification research

In October 2004, experimental research took place at the Great Pyramid concerning the accuracy of the stone blocks fitted into it. The SCA in Cairo kindly granted me permission to use the three calibrated experimental replica ancient Egyptian tools to assess the precision of a random selection of the top surfaces of several core- and casing-blocks fitted into the northern face of the pyramid, together with the only available vertical jointing surface of a huge casing-block located at the base of the same face.[8] These three tools verified that the tested blocks' surfaces are still truly flat and truly horizontal, and that the one casing-block's perpendicular surface is truly vertical. A modern calibrated spirit level confirmed the calibrated replica tools' results. The experiments were filmed by Edgework Media, Washington, DC for a three-part television documentary series entitled, *What the Ancients Knew* for Discovery Communications - The Science Channel. I was the ancient technology consultant for this documentary.

My accuracy verification experiments on some of the Great Pyramid's blocks strongly suggest that three calibrated ancient surface testing tools were present at Fourth Dynasty Giza, and being used to direct the accurate fitting of stone blocks into the Great Pyramid.

These combined tests of anciently calibrated replica tools, being also used to test the accuracy of some of the surfaces of blocks fitted into the Great Pyramid, have never been undertaken before the present experiments related in this chapter.

The replica stone surface testing tools can be viewed on the accompanying DVD, Part 6: Building the Pyramids.

Research impact

My research in this chapter has, for the first time, shown how ancient Egyptian masons precisely fitted the heavy limestone blocks to neighbouring blocks into pyramids, temples and walls and with what tools and techniques for this purpose. This has had a major impact on archaeology in other parts of the world.

Ian Shaw cited five bibliographical publications concerning my experimental stone vessel and faience manufacture, my research on the fitting of stone blocks together, and Pharaonic quarrying operations.[9] Dieter Arnold made numerous citations concerning experimental stone masonry fitting, tools and tubular drilling techniques, together with several bibliographical publications.[10] Galal Ali Hassaan cited stone surface accuracy testing in relation to stonecutting techniques,[11] while John Erwin cited my experimental stone extraction and vase-making techniques as part of his research into Palaeoeskimo quarrying techniques and manufacturing methods for small stone pots at Fleur de Lys, Newfoundland, Canada.[12]

Findings: the presence of three calibrated surface and orientation testing tools, during the building of the Great Pyramid, can be suggested with confidence. My experimental methodology reveals that the pyramid's blocks could *only* have been accurately prepared and laid using the three tools.

Natural phenomena: gravity acting upon the surface of still water and upon a hanging plumb line suspended above it; tension.

Mechanical principles: calibration of assembled tools.

Footnotes:

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Chapter 7

Sliding technology in ancient Egypt

The problem requiring resolution

How did workers haul heavy blocks along level tracks and up and down sloping ramps, and slide blocks over each other when fitting them into walls, temples and pyramids?

Sliding technology for stone blocks and for level and inclined surfaces

Ancient Egyptian masons mitigated the effects of friction and gravity for sliding heavy limestone blocks by employing gypsum mortar as a lubricant.[1] For reducing friction between the runners of a loaded sledge on level surfaces, and on shallowly inclined ascending ramp surfaces, craftworkers utilized a wetted, compacted clay/lime marl track,[2] but *not* for moving objects down steeper, descending tomb corridor surfaces.

In scientific terms[3] the friction that must be overcome to move any stone block is proportional to the coefficient of friction, μ (mu), and the Normal force, N. (The coefficient of friction is a function of the type of surfaces in contact and the Normal force is the vertical force of gravity acting on the block).

The force F required to move a block is $F = \mu N$. If F is taken as the force necessary to *start* sliding, μ is called the coefficient of *static* friction. If F is taken as the somewhat smaller force necessary to *maintain* sliding, μ is called the coefficient of *kinetic* friction: static friction is only considered here. (The coefficient of static friction is the tangent of the *angle* of a ramp on which a block just starts to slide down it. The angle can, therefore, be experimentally measured).

The force required to move a block is independent of the area in contact and, since the weight is fixed, the ease of moving a block can only be altered by changing the coefficient of friction, which is the character of the surfaces in contact. This is what the ancient Egyptians accomplished: they prepared blocks' sliding surfaces to a considerable degree of accuracy, using a lubricant between them, and wetted marl as a lubricant for level and ascending ramp track surfaces.

In order to investigate the sliding characteristics of dry and lubricated horizontal limestone blocks, together with lubricated ascending inclines and dry descending inclines, my experiments began with two prepared limestone blocks and a wooden sledge runner. The prepared experimental limestone blocks' *dry*, accurately flat surfaces were placed in contact, one block above the other, and the bottom block slowly tilted until the top block just began to slide across its surface,[4] the angle of tilt being thirty-six degrees, and also for the dry sledge runner. The tangent of this angle gives a coefficient of static friction of 0.73. The test was then repeated with liquid gypsum mortar applied to the bottom block's top surface.[5] The upper block now commenced sliding at an angle of eight degrees, giving a coefficient of static friction of 0.14, and also for the sledge runner operating on a wetted clay surface.

In January 2010, Atlantic Productions, London filmed two large-scale sliding experiments, organized and conducted by me, that took place on ground situated between Khufu's Great Pyramid and Khafre's pyramid at Giza. The experiments were commissioned by Discovery Communications - The Science Channel for their series called, *Engineering the Impossible – Egypt*. I was the ancient technology consultant for this documentary. Three prepared limestone blocks, each designated top or bottom sliding surface prepared and tested by me to be flat to a tolerance of 0.25 mm, and truly horizontal, were used to determine the ratio of the force necessary to slide a top block's bottom surface over two adjacent lower blocks' top surfaces when dry, and when lubricated with gypsum mortar: each block weighed 130 kg. Dr. Melinda Hartwig, Georgia State University, Atlanta assisted me with both sliding experiments.

I determined that the force required to start to move the upper block, dry, took *five times* the force needed to start to slide it over gypsum mortar, confirming a similar sliding experiment I performed with small blocks in the Manchester workshop: the difference between the dry and lubricated surfaces of the heavy top and two bottom blocks at Giza being emphasized by the top block's swift acceleration on the gypsum mortar lubricant, but using considerably less force than the same dry contacting surfaces.

If the experimentally obtained dry and lubricated coefficients of static friction are respectively substituted in the formula $F = \mu N$, when applied to a base casing-block on the northern face of the Great Pyramid, and weighing 16 tonnes,[6] it can be shown that just over *five times* less force is needed to start a lubricated block moving than a similar dry block, a considerable advantage to the masons. Under the laws of friction this reduction factor applies to all blocks, no matter what their weight and area of surface contact.

Hauling a block on a sledge up a ramp necessitated a balance between the force required and the angle at which slippage occurred. The force needed to haul a block up a slope inclined at the angle of slippage is *twice* that required on the flat.[7] This fact, and the risk of losing a block through slippage, means that the ramp should be inclined at less than the angle of slippage. This explains why the angles of slopes for extant ancient Egyptian ascending ramps are less than eight degrees, the angle of slippage for wet marl lubricated sledge runners.[8]

However, ramps steeper than eight degrees could have been in use by workers for *dry* sliding objects *downwards*, allowing friction and gravity to work in their favour.[9] An example is the ascending corridor of Khufu's Great Pyramid, sloping at just over twenty-six degrees, *down* which three granite plug-blocks were probably dry slid to the bottom, this angle of slope being personally confirmed for this study.

Experiments and calculations demonstrated that moving a heavy object down a sloping, dry limestone surface, which inclined ten degrees *less* than the *dry* slippage angle of thirty-six degrees, required a relatively small increase of force to overcome friction, thus permitting ancient workers carefully and safely to have moved heavy granite blocks down the ascending corridor of the Great Pyramid.

My experimental procedures for testing dry and lubricated sliding phenomena, some carried out at the site of the Great Pyramid, are the first to give comprehensive data concerning the ancient moving of stone blocks for building huge structures.

Research impact

My research in this chapter has, for the first time, shown scientifically, based on my experiments, how ancient Egyptian workers moved stone blocks placed on sledges along flat tracks, or up and down ramps, and how they slid precisely prepared flat surfaces on stone blocks together, which allowed a block easily to be fitted into a building. This has had a major impact on archaeology in other parts of the world.

Elizabeth Bloxam reviewed this chapter's experimental technology in my book, *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, making clear in her review that the manner in which areas of technology – the fitting of stone blocks into structures, for example - were ordered and logical in their presentation.[10]

Findings: almost exactly *five times* less force is needed to start a lubricated block of limestone moving than a similar dry block. A lubricated inclined ramp's surface cannot be angled upwards by more than seven degrees, as slippage occurs at eight degrees.

Natural phenomena: gravity; coefficients of dry and lubricated friction between different materials, such as stone and wood, utilizing the lubricants of gypsum mortar and desert clay/lime marl.

Mechanical principles: lubrication between two surfaces.

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Chapter 8

Metal melting furnaces' air supply technology

The problem requiring resolution

Furnace and metal casting workers needed to make large objects in copper and bronze. How did the workers supply sufficient air to furnaces melting metal in crucibles and how did they ensure adequate metal to be available concurrently in many crucibles?

Fifth, Sixth, Twelfth and Eighteenth Dynasty tomb illustrations

The main limitation to a furnace's ability to melt metal is the volume of air that constantly can be maintained during the melting process. Tomb illustrations in the Fifth Dynasty tomb of Ti, the Sixth Dynasty tomb of Mereruka, the Twelfth Dynasty tomb of Pepionkh and the Eighteenth Dynasty tomb of Hapu depict workers blowing air by reed pipes into furnaces.[1] Without the benefit of wind assistance, and before the foot-operated bellows employed in the Eighteenth Dynasty (see below), melting capacity must have been directly connected to the numbers of workers employed for blowpipe duty.

The common reed, growing profusely along the River Nile, possesses a strong hollow structure. It entered service as a blowpipe for supplying air for early smelting and casting furnaces, although there is no direct proof of when this event occurred. A reconstructed reed pipe, after breaking through the evenly spaced leaf-joint partitions inside its stem, and with one end supplied with a clay/mud heat protective nozzle, supplied air to my project furnace: about 50 l/minute could comfortably be delivered through the experimental pipe. The project furnace, supplied with 200 litres/minute of air by an electric blower, could melt one kilogramme of copper or bronze in a crucible.

In the tomb of Mereruka at Saqqara[2] six men are equipped with blowpipes. This maximum number of workers ever illustrated in Egyptian tombs could supply enough air, if blowing at the experimental rate of 50 l/minute (a total of 300 l/minute), to melt 1.3 kg of copper in a single crucible,[3] sufficient to cast an axe-head displayed in the Manchester Museum (MM 201), and weighing 1.2 kg.[4]

A cluster of furnaces: the key to copper and bronze tools' manufacturing expansion

In order to manufacture a much larger copper casting, for example the long stone-cutting saw for shaping Khufu's Fourth Dynasty granite sarcophagus, many concurrently operated furnaces, about sixteen of them, would have been needed to supply sufficient molten copper for casting the saw blade in a necessary, continuous pouring operation involving, approximately, a calculated ninety-six furnace blowpipe workers to provide such an amount of molten copper.

A method to reduce such a large number of workers, and gain better control over the production of large quantities of molten metal, is revealed in the Eighteenth Dynasty tomb of Rekhmire at Thebes,[5] where two double sets of circular pottery bellows, each set operated by two workers facing each other on opposite sides of a furnace, are illustrated. Both workers are shown with both feet alternately compressing their bellows' diaphragms. My experimental reconstruction[6] demonstrated that considerable volumes of air could continuously be supplied into the furnace through pipes fitted to the four bellows operated in the Rekhmire illustration.

My measurements and calculations revealed that a similar volume of air, equalling the six blowpipes' capability, could now be supplied by a *single worker*. Also, from a health viewpoint, hyperventilation can be experienced as a result of forcing air too quickly through a blowpipe: the foot operated bellows circumvented any threat of hyperventilation, the bellows being a better use of a worker's physical capabilities during extended furnace operation.

There is illustrative evidence of large metal melting capacity in the New Kingdom Period for casting a bronze door in a large mould, indicating the necessary establishment of a *cluster* of furnaces near to the casting site.[7] The tomb of Rekhmire depicts two workers pouring molten metal from a crucible into a funnel, one of twelve pouring funnels projecting upwards from the top of the mould, indicating fast *sequential* pouring of metal along the mould's length by many workers. Unless a sufficient number of crucibles collectively contained enough molten metal it would have been impossible speedily to fill the mould: slow filling prevents a sizeable casting to cool as a coherent solid object.

It is proposed, under these conditions, that a large cluster of furnaces provided many full crucibles, concurrently, in order that a sizable, swiftly executed pouring operation through the twelve funnels could be carried out to cast a successful bronze door.

Such a casting capability is crucial for manufacturing expansion, where the casting of large copper or bronze tools became critical for working intractable materials, for example igneous stone, with large stone-cutting copper and bronze tubular drills and saws.

My experiments concerning reconstructed blowpipes and bellows for test, analysis and evaluation are unique. The furnace cluster theory, and its *raison d'être*, was proposed by me in 2003.[8]

Research impact

My research in this chapter has, for the first time, shown how furnaces for melting copper or bronze in crucibles were supplied with air by up to six blowpipes, which later evolved into efficient foot operated bellows. The chapter has also shown how clusters of concurrently operated furnaces in ancient Egypt were required to provide many crucibles of molten copper or bronze, poured one after the other into big moulds, in order to make large stonecutting tools and other artefacts. This has had a major impact on the field of archaeology in other parts of the world.

Several reviewers of my Publication 14 (2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*) commented upon my discoveries connected with metal casting technology.[9]

Findings: the evidence from ancient illustrations, together with my modern knowledge of casting, strongly indicates the operation of a cluster of furnaces, where necessary, at principal work sites in ancient Egypt.

Natural phenomena: none applicable.

Mechanical principles: none applicable.

Footnotes:

1. Steindorff, G. 1913. *Das Grab des Ti*, Leipzig: Hinrichs, pl. 134; Duell, P. (ed.). 1938. *The Tomb of Mereruka*, Chicago: The University of Chicago Oriental Institute, vol. I, pl. 30; Blackman. A.M. & M.R. Apted. 1953. *The Rock Tombs of Meir*, London: Egypt Exploration Society, pl. XVII; Coghlan, H.H. 1951. *Notes on the Prehistoric Metallurgy of Copper and Bronze in the Old World*, Oxford: Oxford University Press, fig. 10; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 38, fig. 2.20.
2. Stocks, Ibid., 39.
3. Davey, C.J. 1985. 'Crucibles in the Petrie Collection and hieroglyphic ideograms for metal', *Journal of Egyptian Archaeology* 71: 142-8; Petrie,

W.M.F. 1917. *Tools and Weapons*, London: British School of Archaeology in Egypt, 61, pl. LXXVII, W245-8.

4. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 40-1, fig. 2.25.
5. Ibid., 39-40, fig. 2.23.
6. Stocks, D.A. 2007. 'Werkzeugkonstrukteure im Alten Ägypten', *Sokar* 15 (2/2007): 76, note 16.
7. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 34-43, fig. 2.24.
8. Ibid., 34.
9. Bloxam, E. Spring 2004. *Egyptian Archaeology*, EA24, 43, reviewed: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge; Hassaan, G.A. April 2016. 'Mechanical Engineering in Ancient Egypt, Part XXII: Stone Cutting', in *International Journal of Advanced Research in Management, Architecture, Technology and Engineering* (IJARMATE), vol. 2, Issue 4, 223-33. He included a bibliographical publication: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge; Raepsaet, G. 2005. *L' Antiquité Classique*, T. 74, 582, reviewed: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.

Chapter 9

The Twelfth Dynasty quick-release, counterweighted tourniquet wooden lever: increased production of ships' planks

The problem requiring resolution

The device for sawing planks off large pieces of timber, seen in tomb illustrations, has never been located by archaeologist. How did this device operate and what effect did it have on increasing the rate of sawing wood?

The Twelfth Dynasty counterweighted tourniquet wooden lever

An interesting invention in use with serrated copper saws is depicted in several tombs, notably at Twelfth Dynasty Deshasheh and Meir.[1] The equipment shown consists of a vertical post buried in the ground, to which a vertical piece of timber is first loosely lashed with a rope. Inserted into this slack lashing is one end of a short wooden rod - a lever. Rotating the lever – now a *tourniquet* lever - tightens the lashing. Also illustrated is a stone counterweight suspended on a rope near to the rod's opposite end. After carrying out the tourniquet lever's tightening rotation, the illustration suggests that the stone weight can be adjusted along the lever's length, automatically keeping the lashing tight. The lever, ideally, should now be in a horizontal position, the sawyer's hands both being free to operate a saw.

My experiments with a reconstructed rod, weight and rope lashing[2] demonstrated that, by sliding the weight along the rod, the equipment could indeed maintain the tension on the rope lashed around the post and the timber. The timber is, consequently, firmly held and could vertically be sawn to detach a plank from it.

But by temporarily sliding the rope and weight off the rod, it acted as a quick-release mechanism, allowing the rope lashing to loosen when timber needed sliding up the post as sawing continued downwards.

I erected a counterweighted tourniquet lever in a garden adjacent to the Pharaonic Village's ancient technology exhibition and demonstration area in Cairo. Extensive sawing tests were carried out by a trained operative. The tests showed that this tool's ability rapidly to tighten, and then to slacken, the rope's lashing could be achieved with little effort in a second or two.

My reconstructed device is the first one built for test, analysis and evaluation.

The quick-release - then retighten - mechanism permitted a single sawyer to use *both* hands to push and pull the saw, thereby detaching a plank off the timber in a much shorter time period, releasing a once necessary helper similarly to saw another plank at a nearby location using their own tourniquet lever device.

Research impact

My research in this chapter has, for the first time, shown how ancient Egyptian wood sawyers used a device for sawing thick planks off tree trunks, which allowed a single operator to achieve this heavy work without assistance. This has had a major impact on archaeology in other parts of the world.

Klaus Richter reviewed the counterweighted tourniquet lever technology, commenting upon the efficiency of the tighten and quick-release device.[3]

Findings: numerous quick-release, counterweighted tourniquet lever devices, particularly at a ship-building site, allowed a more rapid manufacture of planks.

Natural phenomena: tension; friction; leverage; torque; gravity.

Mechanical principles: adjustment.

Footnotes:

1. Blackman. A.M. & M.R. Apted. 1953. *The Rock Tombs of Meir*, London: Egypt Exploration Society, pl. XVIII; Petrie, W.M.F. 1898. *Deshasheh*, London: Egypt Exploration Fund, pl. XXI; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 67-9, figs. 2.57, 2.60.
2. Stocks, Ibid., 68, figs. 2.58, 2.59.
3. Richter, K. 2005. *Sokar*, vol. 5: 41-3, reviewed and cited a bibliographical publication: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.

Chapter 10

The Twelfth Dynasty interchangeable tool drill-stock: a wood-working and fire-making device

The problem requiring resolution

Wooden drill-stocks, dated to the Twelfth and Eighteenth Dynasties, were located by Flinders Petrie and Howard Carter. There are indications that this tool played a key rôle in drilling materials. How was this tool constructed and how did it function?

A replica interchangeable tool drill-stock

During Flinders Petrie's excavations at the Twelfth Dynasty workers' town of Kahun he discovered a bow-driven wooden drill-stock, now displayed in the Manchester Museum (MM 23):[1] he also excavated one at Eighteenth Dynasty Gurob.[2] Howard Carter found a similar drill-stock in the Eighteenth Dynasty tomb of Tutankhamun,[3] a small wooden fire-stick still force-fitted into position at the drill-stock's lower end.

A drawing of the Kahun drill-stock[4] shows the upper end carved into a central peg, upon which fitted a wooden bearing cap; the arrangement allowed the stock freely to turn when rotated with a bow. The stock has flat faces carved around its double-tapered circumference, and these extend for the whole length of the tool. Tutankhamen's drill-stock had also been carved in a similar fashion. The Gurob stock is similar in all respects to the Kahun and Tutankhamun's drill-stocks, but had not been carved with flat faces. What were these adjacently carved faces for?

My experimentally manufactured replica drill-stock[5] demonstrated that the provision of flat faces around the stock's waisted, double-tapered circumference increased the necessary tight grip of the driving bow's string. Also, allowing a stretched bow-string to engage on a wider diameter, up or down the stock, enabled it automatically to increase its grip. Tests indicated that a fire-stick needed to be spun rapidly in order to generate enough hot ash to start a ball of dried grass to smoulder, and eventually to burst into flame by gently blowing into it.

The stock also has a short vertical hole drilled upwards into its body, commencing from the centre of the bottom flat end. Its purpose definitely included the insertion of an interchangeable fire-stick, as in Tutankhamun's drill-stock: burnt and shortened sticks could be ejected out of the vertical hole with a slim rod, possibly made of copper, poked down an inclined ejection hole, which connected the drill-stock's circumference to the blind end of the vertical hole. It is likely that this ejection hole allowed the interchange of a copper drill for wood[6] and, probably, a flint drill for other purposes, such as boring. The tool interchangeable drill-stock, therefore, saved making three separate bow-driven tools to spin either a permanently fitted copper drill, or a flint drill, or a fire-stick.

The technological change to a drill-stock, from a fire-stick, continued the practice that interchanging parts that suffered wear during fire-making was necessary to conserve the main tool in which a considerable amount of time and energy had been invested. Similarly, broken flint drills and worn copper drills could also be replaced with a minimum of effort and cost. This tool follows the interchangeability techniques incorporated in the construction of the stone vessel manufacturing Twist/Reverse Twist Drill.

This replicated drill-stock is the only one to have been manufactured for the full tests and analyses summarized above.

The replica drill-stock can be seen operating in the accompanying DVD, Part 3: Making Tools from Copper, Replaceable Fire Drills.

Research impact

My research in this chapter has, for the first time, shown how the ancient Egyptians invented a multi-purpose drilling tool, which permitted a speeding up drilling operations. This has had a major impact on archaeology in other parts of the world.

Georges Raepsaet reviewed this technology, and technology aspects accompanying drilling techniques,[7] and Jiang, H., Feng, G., Liu, H.C., Weng, S., Ma, L. & D.K. Ferguson have been studying the fire drills excavated in the Yanghai cemetery (c. 1000 BCE – c. 100 CE) of ancient Turpan, China. The authors cited my experimental fire-sticks' results in order to reference them to the fire drill types found in the Turpan cemetery.[8]

Findings: the introduction of the interchangeable drill-stock improved manufacturing capability, replacing previous, dedicated wooden shafts designed only for *either* fire-making, *or* for drilling purposes.

Natural phenomena: friction; tension.

Mechanical principles: rotary motion; interchangeability; adjustment between a stretched bow-string and a tapered, waisted drill-stock.

Footnotes:

1. Petrie, W.M.F. 1890. *Kahun, Gurob and Hawara*, London: Kegan Paul, Trench, Trübner, and Co., 28, pl. IX; Stocks, D.A. 2001c. 'Tools', in Redford, D.B. (ed.), *The Oxford Encyclopedia of Ancient Egypt*, New York (NY): Oxford University Press, vol. 3, 442, fig. 1.
2. Petrie, W.M.F. 1890. *Kahun, Gurob and Hawara*, London: Kegan Paul, Trench, Trübner, and Co., 14, pl. XVIII; Petrie W.M.F. 1917. *Tools and Weapons*, London, British School of Archaeology in Egypt, pl. XLIII, M7; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 54.
3. Carter, H. 1933. *The Tomb of Tut.Ankh.Amen*, London: Cassel, vol. III, pl. XXXVIII; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 53-4.
4. Stocks, Ibid., 54, fig. 2.46.
5. Stocks, D.A. 2002. 'Technical and material interrelationships: implications for social change in ancient Egypt', in W. Wendrich and G. van der Kooij (eds.), *Moving Matters: Ethnoarchaeology in the Near East. Proceedings of the International Seminar held at Cairo, 7-10 December 1998*, Leiden: Research School of Asian, African, and Amerindian Studies (CNWS), Universiteit Leiden, The Netherlands, 111.
6. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 54.
7. Raepsaet, G. 2005. *L' Antiquité Classique*, T. 74, 582, reviewed: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.
8. Jiang, H., Feng, G., Liu, H.C., Weng, S., Ma, L. & D.K. Ferguson. 2018. 'Drilling wood for fire: discoveries and studies of the fire-making tools in the Yanghai cemetery of ancient Turpan, China', *Vegetation History and Archaeobotany*, vol. 27, Issue 1: 197-206. The authors cited, Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 53, figs. 2.44, 2.45, 54, fig. 2.46.

Chapter 11

Mass-production processes in ancient Egypt

The problem requiring resolution

Several New Kingdom tomb illustrations of a single worker operating a bow turning several drills for perforating stone beads can be seen at Thebes, Upper Egypt. None of this drilling equipment has been located by archaeologists. Reusable, fired moulds for casting copper and bronze tools, and moulds for making faience cores, indicate mass-production methods were employed to increase the rate of manufacture for beads, for casting identical tools and for repeating favoured designs of faience objects. But how were complex tools for multiple drilling techniques designed and built?

New Kingdom multiple bead-drilling equipment at Thebes, Upper Egypt

At Thebes, Upper Egypt, six Eighteenth and Nineteenth Dynasty private tombs[1] contain illustrations showing a single craftworker simultaneously drilling several stone beads, indicating that the previous single bow-driven copper and bronze bead-drill[2] evolved into a *mass-production* multiple bead-drilling tool.

In the representations, each operator is simultaneously perforating at least two beads, but sometimes three, four, or even five beads are being drilled at the same time by a single worker using a long, curved bow. These changes not only required fundamental modifications to single drills, but also in the manner in which multiple bead-drilling tools could be operated.

Examining the tomb illustrations suggests that the drilling equipment consists of the bow; its string is wound around each of several small-diameter cast bronze drill-rods, each revolving in a bearing hole upwardly drilled into the bottom end of a wooden stick. The multiple bead-drilling tool most clearly depicted is the Eighteenth Dynasty tomb of Rekhmire. In this illustration, the driller sits closely to a three-legged wooden table: the table's top contains the beads in a line, equally spaced apart, and either forced into appropriately drilled holes, or set into a hollow table-top filled with soft mud. In my experimental reconstruction the mud, when dry, immovably held the beads.

The three wooden sticks in the Rekhmire illustration, held in a line by the worker, permitted the drill-rods' points, after the bow-string had been turned loosely around each rod, to engage into three scraped depressions created in the beads' polished surfaces by a flint tool.[3] My working reconstructed tool, based upon the Rekhmire illustration, was built for its experimental operation, analysis and evaluation. It is the only reconstructed multiple bead-drilling tool ever built for experimentation, and the results published for examination by archaeologists.

My first experiment concentrated on how quickly the tool could be assembled in the correct order; indeed, could the tool be assembled by its operator alone, or was assistance required? The three drill-rods, with the bow-string wound in turn around each rod, needed the three sticks to be placed onto each drill-rod. Tightening the string proved to be slightly more difficult. It is clear that a driller needed considerable manual dexterity in both hands. However, my tests proved that the multiple bead drill could be assembled for use by a single person.

For the experimentally reconstructed tool to operate a runny paste, made of waste, finely ground sand/stone/copper particle drilling powder and muddy water, was spooned onto each of the beads at the point of drilling. The bow-string, when tightened around the rods, and driven forwards and backwards by the reciprocating action of the bow, rotated each drill *simultaneously*: the bow's driving hand's thumb, pushed between the bow-shaft and the string, could be used continually to adjust the string's tension, and thus its ability more tightly to grip each drill-rod's circumference if slippage occurred.[4] Prolonged test drilling, carried out in the Pharaonic Village, Cairo, revealed that the string slowly polished each bronze drill-rod's circumference, its increasingly inadequate grip on the rods allowing considerable slippage.[5] Periodic roughening of the rods' surfaces cured this difficulty.

My reconstructed simultaneous multiple bead-drilling tool's rigorous testing in the Pharaonic Village's ancient technology demonstration area by a trained person discovered the slippage problem outlined above, a difficulty not revealed during initial short test periods in the UK workshop.

This equipment, when considering the Rekhmire depiction, allowed three amethyst spherical beads to be drilled simultaneously with a threading hole in almost the same time as a similar diameter hole could be accomplished by a single bead-drill, substantially reducing the cost of stone bead manufacture for jewellery production.[6] Further, the tomb of Sebekhotep shows *four* craftworkers operating their multiple drilling tools in a workshop, truly a mass-production process in the New Kingdom jewellery business.

The multiple bead-drilling tool can be seen operating in the accompanying DVD, Part 4: Drilling Hard Stones & Beads, and Part 5: Advanced Drilling.

Reusable open pottery moulds for metal casting, and for moulding separate, open, front and back parts of faience cores

Before the advent of the New Kingdom multiple bead drilling tool, Twelfth Dynasty reusable open pottery moulds allowed the *mass-production* of cast copper chisels, and other tools, at the workers' town of Kahun,[7] increasing their availability for work.

As a result of this technical change in casting from open, single-use sand moulds, it is likely that a cluster of furnaces could now be operated to supply greater quantities of molten copper or bronze for casting an increased quantity of important tools. Consequently, more workers could be furnished with tools, thereby increasing the economic output of the Egyptian state due to the expansion of artefact production.

Similarly, many thousands of pottery moulds for faience beads, pendants, scarabs and shawabtis have been found at numerous sites in Egypt by Flinders Petrie, and others.[8] Moulds were open, so separate ones were needed for the front and the back of a faience core,[9] which craftworkers joined together with moist paste before glazing took place. An accepted prototype of any faience object could be mass-produced, using a selected and authorized master mould, and multiple copies of it.

Research impact

My research in this chapter has, for the first time, shown several types of mass-production – drilling stone beads' threading holes with a simultaneous, multiple bead drill operated by a single worker, and the use of reusable moulds for mass-producing copper and bronze castings and faience cores. I have made a major discovery that has had a major impact on archaeology in other parts of the world.

Nacho Ares wrote a review article concerning experimental simultaneous multiple stone bead perforation and its consequences for expanding production of jewellery in ancient Egypt.[10]

Findings: the mass-production principles of drilling threading holes into hard stone beads, and the reusable pottery moulds for mass-producing identical copper castings and identical faience artefacts.

Natural phenomena: friction; torque; tension.

Mechanical principles: adjustment between the bow-string and the bronze drill-rods; top and bottom bearings for revolving bead-drills; reciprocating and rotary motion.

Footnotes:

1. Wreszinski, W. 1923. *Atlas zur altägyptischen Kulturgeschichte*, Leipzig: Hinrichs, vol. I, pls. 73, a, b, 154, vol. II, pls. 242, 313, 360; Davies, N. de G. 1922. *The Tomb of Puyemrê at Thebes*, New York: Metropolitan Museum of Art, vol. I, pl. XXIII; Newberry, P.E. 1900. *The Life of Rekhmara*, London: Archibald Constable, pls. XVII, XVIII; Davies, N. de G. 1943. *The Tomb of Rekh-mi-Rē' at Thebes*, New York: Metropolitan Museum of Art, vol. II, pl. LIV; Davies, N. de G. 1923. *The Tombs of Two Officials of Tuthmosis IV at Thebes*, London: Egypt Exploration Society, vol. II, pl. X; Davies, N. de G. 1925. *The Tomb of Two Sculptors at Thebes*, New York: Metropolitan Museum of Art, pl. XI; Stocks, D.A. 1989a. 'Ancient factory mass-production techniques: indications of large-scale stone bead manufacture during the Egyptian New Kingdom Period', *Antiquity* 63: 527, fig. 1a; Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 208-9, figs. 8.6-8.8, 210, fig. 8.10; Stocks, D.A. 2015. 'Some experiments in ancient Egyptian stone technology', in C. Graves-Brown (ed.), *Swansea Conference – Experiment and Experience: Ancient Egypt in the Present*, Swansea: Classical Press of Wales, 186, fig. 7.
2. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 205-6, figs. 8.1, 8.2.
3. Ibid., 218, fig. 8.20.
4. Ibid., 219, fig. 8.22.
5. Stocks, D.A. 2015. 'Some experiments in ancient Egyptian stone technology', in C. Graves-Brown (ed.), *Swansea Conference – Experiment and Experience: Ancient Egypt in the Present*, Swansea: Classical Press of Wales, 193, fig. 10.
6. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 205, table 8.1B.
7. Petrie, W.M.F. 1890. *Kahun, Gurob and Hawara*, London: Kegan Paul, Trench, Trübner, and Co., 29.
8. Petrie, W.M.F. 1894. *Tell el-Amarna*, London: Methuen, 30.
9. Lucas, A. & J.R. Harris. 1962. *Ancient Egyptian Materials and Industries*, London: Edward Arnold, 159.
10. Ares, N. (ed.), July 2002. Review article, 'Entrevista con Denys Allen Stocks', *Revista de Arqueologia*, vol. 21, 64-8, by the editor, Nacho Ares. Publications consulted by the editor: Stocks, D.A. 1999a. 'Stone vessels and bead making', in K.A. Bard (ed.), *Encyclopedia of the Archaeology of Ancient Egypt,* London and New York: Routledge, 749-51; Stocks, D.A. 1999b. 'Stone sarcophagus manufacture in ancient Egypt', *Antiquity* 73: 918-22.

Chapter 12

The adjustable Eighteenth Dynasty tripod anvil

The problem requiring resolution

An Eighteenth Dynasty tomb representation shows an anvil possessing three legs, with a vessel placed in an upside down position upon the top of it. What is this tripod anvil for and how was it constructed and with what materials?

Reconstructing and experimenting with a tripod anvil

An illustration in the Eighteenth Dynasty tomb of Rekhmire at Thebes, Upper Egypt[1] depicts metal workers using *hemispherical* hand-held stone hammers for beating vessels of precious metals to shape, which are placed upside down on a tripod anvil. Craftworkers also portray the beating of metal vases with the *flat* side of the hemispherical hammer, as well as with its curved surface. Probably, stone vessels were also mounted upon the anvil for smoothing their exteriors with stone grinders and polishers.

Using the illustration in the tomb of Rekhmire as a guide, I manufactured a reconstructed New Kingdom anvil consisting of a forked tree branch, the forked end being placed on the ground at an acute angle. A long wooden rod, the third 'leg' of this device, passes easily through an upward slanting hole drilled into the upper, single stem. The Rekhmire illustration unmistakably depicts a clearance hole for accommodating the wooden rod.

My use of this large tool, the first one to be built for experiments, revealed that, if weight is placed on the tripod formed by the tool's construction, it immediately 'locks' into the position set by a worker: stability is assured, as any three-legged object is quite steady on uneven ground. This allows the tool to be *adjusted* in order to beat both large and small metal vessels:[2] the adjustability of the tripod anvil saved the considerable time and effort to make separate *fixed* tripod anvils for various shapes and sizes of both metal and stone vessels, thus saving materials and manufacturing time. Multiple anvils, located in one location, permitted increased production of metal and stone vessels.

It is likely that the end of the rod, when in use for silver and gold vessels, could have been fitted with interchangeable padded heads, possibly made of leather, which were either curved and/or angular in shape.

Research impact

My research in this chapter has, for the first time, shown how the ancient Egyptian craftworkers fashioned metal vessels upon a wooden tripod anvil, also using it as a device for supporting stone vessels whilst smoothing and polishing their exterior surfaces. This has had a major impact on archaeology in other parts of the world.

Georges Raepsaet reviewed this technology, and the ability of ancient craftworkers to invent tools to assist difficult manufacturing operations, such as shaping metal and stone vessels.[3]

Findings: the use of this ingeniously designed anvil allowed all sizes of metal vessels to be beaten to shape, including the finishing of stone vessels' exteriors.

Natural phenomena: friction between two surfaces, which allowed the anvil's weighted 'leg' immovably to be held by the forked shaft; gravity.

Mechanical principles: adjustment.

Footnotes:

1. Davies, N. de G. 1943. *The Tomb of Rekh-mi-Rē' at Thebes*, New York: Metropolitan Museum of Art, vol. II, pl. LIII.
2. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 46-7, figs. 2.31-2.33.
3. Raepsaet, G. 2005. *L' Antiquité Classique*, T. 74, 582, reviewed: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.

Chapter 13

The yarn twisting tool for making string and rope

The problem requiring resolution

An illustration in the Eighteenth Dynasty tomb of Rekhmire depicts a tool being used to twist yarns together. No examples of this tool have been found by archaeologists. How did it operate, and was it successful in producing good quality twisted yarns in a much shorter time period than twisting yarns together by hand?

A reconstructed yarn twisting tool

String and rope were made from a variety of natural materials, and these included camel hair, halfa grass, flax, and date palm fibres, as well as linen, papyrus and leather.[1]

Emily Teeter[2] has summarized manufacturing methods for yarns, string and rope. The first step involved the making of yarns from fibres or grasses, which were all twisted in the same direction. Secondly, the craftworker twisted yarns around each other in the opposite direction. The first yarn twisting, and possibly the twisting of the yarns together into the final product, was achieved by a worker first securing them at one end, the opposite ends of the yarns being either twisted by hand, in earlier times or, later, by a worker using a tool invented for this purpose.

Such a tool is illustrated in the Eighteenth Dynasty tomb of Rekhmire.[3] It depicts two yarns, each one being necessarily tied separately to each end of a short wooden bar: as the later experimental tests suggest, secure separation is vital for the tool's successful operation. The scene portrays a belt around the worker's waist, possibly made of leather.[4] This worker is *leaning* backwards to exert tension on the yarns as he spins them around and around each other to twist them together: the other ends must firmly be held some distance away by another worker, or tied to a post fixed into the ground, its position dictated by the required length of the finished twisted yarn.

The belt's two ends are depicted tied to the end of a rod; the ends are prevented from slipping off by a larger diameter section at the rod's end, which is taking the strain of the operator's leaning action. This rod is probably made from wood, and the operator forcefully extends it straight out to the belt's limit of movement; the rod is long enough to be held at its centre position by a clenched hand. A spherical weight, secured to a short straight rope, is tied to one end of the bar. The rope would be straight, as depicted by the artist, if the bar was spinning rapidly on the rod, centrifugal force tensioning the rope. The artist froze the bar's rotation to draw the spherical weight on a straight rope.

Accepting these observations to be reasonable led to my experimentally reconstructed tool's rod to *loosely* fit into a hole drilled completely *through* the centre of the bar. For the yarn twisting tool, the rod's diameter at the bar's surface *forwards* from the operator necessarily increased, otherwise the bar would have come off the rod under the tension applied by the operator's *backwards* leaning position, and the tension in the yarns *in front* of the bar.

My working reconstruction, the first tool manufactured for experimental use, revealed that this left-handed worker is gripping the rod hard and rotating it extremely quickly and energetically in very small circular movements. Under this action the loosely fitted rod within the bar's hole transmits a turning motion to the bar through friction between the rod's exterior circumference and the bearing hole's internal circumference, causing the bar rapidly to revolve and twist the two yarns together at an impressive rate. The rod can be rotated clockwise or anticlockwise, dependent upon the twist required. The tool's single weight exerted a considerable centrifugal force, conserving the bar's rotating momentum, as well as overcoming the resistance of the two yarns twisting together.

A demonstration of my reconstructed yarn twisting tool, by Dr. Joyce Tyldesley, trained by me, can be viewed on the accompanying DVD, Part 7: Making Rope.

Research impact

My research in this chapter has, for the first time, shown how the ancient Egyptians increased the rapid and efficient twisting of yarns together for weaving, and for making string and rope. This has had a major impact on archaeology in other parts of the world.

Elizabeth Bloxam reviewed this technology, drawing attention to the manner in which other, associated areas of technology, particularly the display of ancient inventiveness, is presented to the reader of my research.[5]

Findings: this tool is a remarkable ancient invention that must dramatically have increased the ancient rate of yarn, string and rope manufacture.
Natural phenomena: centrifugal force; momentum; friction; tension.

Mechanical principles: shaft and bearing; rotary motion.

Footnotes:

1. Lucas, A. & J.R. Harris. 1962. *Ancient Egyptian Materials and Industries*, London: Edward Arnold, 134-5.
2. Teeter, E. 1987. 'Techniques and terminology of rope-making in ancient Egypt', *Journal of Egyptian Archaeology* 73: 71-7, pls. VII, 3, VIII, 1, 2, IX.
3. Davies, N. de G. 1943. *The Tomb of Rekh-mi-Rēʿ at Thebes*, New York: Metropolitan Museum of Art, vol. II, pl. LII; Stocks, D.A. 2007. 'Werkzeugkonstrukteure im Alten Ägypten', *Sokar* 15 (2/2007): 79, Abb. 13.
4. Stocks, D.A. 2001a. 'Leather', in D.B. Redford (ed.), *The Oxford Encyclopedia of Ancient Egypt*, New York (NY): Oxford University Press, 283.
5. Bloxam, E. Spring 2004. *Egyptian Archaeology*, EA24, 43, reviewed: Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.

Chapter 14

Discussion and Conclusions

Natural phenomena and mechanical principles (2)

During a mechanical engineering technical apprenticeship I was trained to design and manufacture, by hand, tools for specific mechanical engineering purposes, in which I took note of natural phenomena affecting a modern tool's construction, for example friction. Although the laws of *static* and *dynamic* friction were then unknown to me, trial and error gradually satisfied the manufacturing parameters surrounding a particular tool's projected use, and that adjustments to experimental mock-ups, following established mechanical principles, would eventually iron out problems to the satisfaction of my mentor.

It is likely that ancient Egyptian tool-making followed a broadly similar procedure. For example, limestone blocks being laid into the Great Pyramid always required a block's bottom and top surfaces to be truly flat and horizontal in all directions, and also parallel to each other. The project research and experiments suggest that craftworkers designed a tool for testing whether a flattened block's top surface was truly horizontal after being laid, this tool being based upon the two natural phenomena that still water in a container is always flat and horizontal in all directions, and that a stationary, hanging plumb line is always vertical to a flat water's surface and, therefore, at right-angles to the plumb line for a full circle around it.

The flat water's truly horizontal surface could have been visualized in ancient times as a block's finished top surface, but there was no need to know *why* still water is always flat and horizontal, or whether a hanging plumb line is always truly vertical to the water's surface. Craftworkers observed two natural phenomena that *never varied*, using them to create a simple and accurately calibrated surface testing tool.[1] My experiments in Chapter 6 indicate its use at the Great Pyramid.

Indicated technical and material interrelationships

1. At the beginning of Chapter 2, it was suggested that five copper tools - the chisel, the adze, the saw, the knife and the hafted axe – owed their shapes to four Predynastic cutting tools, namely the flint end-scraper, the denticulated flint sickle, the flint knife and the stone hand-axe, which were used for working a variety of

natural materials, including wood and stone, before the introduction of cast copper at the commencement of the Nagada II Period, c. 3600 BCE.[2]

The flat-tapered copper chisel and adze permitted improved performance and life for the tools, as well as improved production of artefacts, such as limestone blocks and wooden objects. Yet there is evidence of similar flint, copper and bronze tool shapes being used alongside each other at Twelfth Dynasty Kahun and at Eighteenth Dynasty Gurob, both towns located in Lower Egypt near to the Fayum,[3] and this situation represents an interesting, productive interrelationship between the contrasting materials of flint, copper and bronze.

This interrelationship between sharp copper and bronze tools, and even sharper flint tools, is an even deeper one: each copper tool is, in fact, complementary to a sharp-edged tool of flint, and vice versa, because awkward places needing a precise, clean cut in pliant materials can be executed with a flint tool, whereas metal chisels, or the similarly shaped adze, are more useful, initially, for removing much larger areas of, for example, soft limestone or red sandstone. The flint tool is, however, much more capable of cutting sharply defined, incised and low relief hieroglyphs into a prepared limestone surface than a sharp metallic tool. Project experimental manufacturing of tools, and other artefacts, often employed copper or bronze chisels, and flint chisels, or other shaped flint cutting edges, for completing the same artefact, but expendable flint chisels and punches are the only tools that could experimentally cut hieroglyphs into igneous stones, such as granite. Therefore, it is likely that ancient craftworkers also enjoyed a creative partnership between metal and flint implements.

2. An interrelationship between nature's reed architecture and two critically essential tools – the reed blowpipe for the delivery of air into a furnace, and the reed tube for drilling holes in softer stones - is clearly shown in the designs for these tools: the importance of the common reed growing alongside the River Nile, as the original design shape for two crucial industrial tools, one copied in copper for drilling the hardest stones, cannot be over-emphasized.

The reed blowpipe, the reed tubular drill, and its copy in copper, and later in bronze, fundamentally changed the direction of ancient Egyptian technology. Without the furnace blowpipe, which eventually evolved into the much more efficient New Kingdom foot-operated bellows, the smelting of significant amounts of copper from its ores, and the subsequent melting of sufficient copper for casting into useful tools, and other artefacts, would have been much more difficult to accomplish if funnelled wind, *solely*, had been relied upon to sustain the necessary temperature of a furnace. And without the copper tubular drill there would not have been an efficient and reliable method of hollowing the hardest stone artefacts, whether they were small basalt vessels, or huge granite sarcophagi.

3. The indispensable copper stone-drilling *flat-ended* tubular drill, and the equally essential stone-cutting *flat-edged* copper saw, both operating on sand abrasive, shared two manufacturing and operating procedures.

A tubular drill, if flattened out from its vertical joint, becomes a short, flat-edged saw blade but, conversely, a thin saw blade can be rolled around a wooden former into a tubular drill. In fact, many tubular drills, and stone-cutting saw blades, started their lives as cast copper sheets, later beaten thinner on a stone anvil.[4]

Drill-tubes and saws fundamentally operated using reciprocating motion: the saw directly, the tubular drill by converting reciprocating motion into rotary motion by a bow-string or a bow-rope wound around the smaller or larger circumferences of the wooden shafts driven into them. But, interestingly, the copper or bronze tubular drill was also fitted to a Twist/Reverse Twist Drill's central wooden shaft for drilling out hard and soft stone vessels. These twin drill-tube driving methods for hollowing large artefacts, in addition to smaller, more delicate stone vessels, reveals how interrelated these critically important, wealth-producing tools were to the ancient Egyptians.

4. The evidence for sand being the abrasive employed with ancient copper tubular drills and copper saws for working stone is well established,[5] which must continually have created large volumes of waste powders composed of sand, stone and particles of copper. Such immense volumes of waste powders are robustly implied by my experimental use of copper tubes and saws operating on different stone types with sand abrasive in Manchester, UK, but more especially the full-scale drilling and sawing of rose granite experiments carried out in Aswan in 1999.[6]

My experimentally manufactured, scientifically tested faience cores and glazes, using these waste (by-product) powders, undoubtedly indicate that they are similar in significant, and essential, respects to ancient faience cores and blue and green glazes, revealing a clear-cut, convincing interrelationship and interdependence between these two separate, and quite different, industries.

Implications for social evolution in ancient Egypt[7]

The drilling and sawing experiments on travertine, some varieties of limestone, plus the harder stones, such as igneous granite and basalt, indicate the constant attrition of copper from the stone-cutting tubular drills and saws, and which also created many thousands of tonnes of waste sand/stone/copper-contaminated powders. These, in turn, provided the raw materials for the huge industry of making faience cores, blue glazes, frits and pigment, and for the fine grinding and polishing procedures for finishing stone objects, and for drilling threading holes in stone beads, which compellingly suggest that these two widespread, interrelated industries of manufacturing stone vessels, sarcophagi, statuary, and other stone artefacts requiring sawing and hollowing procedures, together with faience production, were key to the development of early Egyptian technology and manufacturing capability, commencing in the Predynastic Period and continuing until the end of Egyptian civilization.

The severe abrasion rate of copper ground from the experimental, large-scale copper saw and copper tubular drill, employed during the experimental Aswan rose granite sawing and drilling tests, strongly indicate that workers were obliged continuously to smelt and cast sufficient copper to replace stone-cutting saws and tubular drills constantly ground away throughout millennia of drilling and sawing hard stone: there was no other manner in which ancient workers could hollow, for example, a hard stone sarcophagus, or saw one to shape. The evidence for a single slag heap, resulting from the smelting of 5,500 tonnes of copper, suggests how unremitting was the constant replenishment of copper required for stone-cutting tubular drills and saws, illustrating the remarkable resilience and manufacturing capability of an increasingly powerful ancient Egyptian economy.

All of the technical evidence contained in my published work indicates the establishment of an innovative, complex, progressive and interrelated industrial society that became sufficiently developed in the Predynastic Period to supply significant numbers of valuable artefacts, particularly stone vessels, which themselves became an enduring cornerstone of Egyptian wealth production.

A number of important inventive technical steps, for example the New Kingdom mass-production of stone bead perforation, progressively increased the creation of artefacts, accompanied by a reduction of manufacturing times:[8] technical improvements slowly adjusted the configuration of Egyptian society. These factors decreased costs, making artefacts accessible to wider, and more numerous groups of people, gradually transforming the organization of workers who were required either to move location, and/or be retrained to make and use new tools to create different artefacts. Considerable numbers of workers must have been relocated to toil in faraway places, particularly for large-scale state building projects. Inevitably, these intermittent measures sporadically changed society's previous, but always relatively short-lived, overall settled cohesion, irregularly varying and modifying the direction and tempo of Egypt's social evolution.

These factors imply an all-encompassing, nationwide organization evolved to implement and administer pivotal industrial procedures, such as the mining and smelting of copper ores and the casting and transportation of copper ingots to work centres.

The most notable technical advances were the conversion of specific flint tools into copper; the modification of the reed tube into a blowpipe and a drill-tube for making holes in soft stones, later copied in copper and driven with the bow and the Twist/Reverse Twist Drill for working hard stones; the casting and beating of stone-cutting and wood-cutting copper and bronze saws; the employment of by-product sand/stone/copper-contaminated powders for making faience cores, blue glazes, frits and pigments, and as a fine abrasive for polishing stone and for drilling threading holes in stone beads; the manufacture of copper, bronze, iron and flint chisels, adzes, punches and scrapers; the creation of clusters of furnaces for casting large metallic objects and the fashioning of reusable pottery moulds for mass-producing identical metal castings and faience artefacts.

Other helpful inventions included the interchangeable tool drill-stock; three accurately made surface testing tools; the use of sliding phenomena with regard to lubricated inclined upward surfaces, and the sliding of lubricated stone blocks into place; expendable flint tools; the quick-release, then retighten, adjustable counterweighted tourniquet lever; the New Kingdom yarn twisting tool; the adaptation of tree branches to make bows, Y-shaped woodworking supports, tripod anvils and TRTD main shafts, together with their associated forked shafts for driving stone borers; the New Kingdom multiple, simultaneous bead-drilling equipment; the establishment of workshop mass-production methods.

The gradual formation and development of industrial processes required the employment of ever-increasing numbers of administrators and clerks to control the workers, and their tools, and consumed continually increasing amounts of materials.

The making of *multiple numbers* of different specialized tools (e.g. the stone vessel drilling and boring tool, the tripod anvil, the yarn twisting tool and the quick-release, counterweighted tourniquet lever), and their *concurrent* use by numerous skilled operators for these implements at *one* specific manufacturing or building location, allowed the construction of, for instance, a large ship made of wooden planks stitched together with ropes, or massive pyramids and temples needing immense numbers of fitted stone blocks. Overseers must have controlled the provision of ever-increasing amounts of dissimilar material types.

The personal costs to workers need to be mentioned.[9] The indications of serious, life-threatening lung disease caused to workers engaged in drilling and sawing stone with sand abrasive, especially those workers manufacturing both soft and hard stone vessels, seriously limited the length of their working lives by inhaling micron-sized quartz fragments. The use of flint chisels and punches for working hard stone, particularly for cutting hieroglyphs, risked eye injuries to workers. Furnace workers were vulnerable to spills of molten copper onto their legs and feet, and to the inhalation of large volumes of fumes and smoke at furnace sites. Workers using many different types of tools, particularly chisels and mallets, must have suffered repetitive strain injuries to their hands and wrists over protracted time periods. Hyperventilation, causing dizziness and exhaustion, may have been a problem to some workers blowing air through blowpipes.

My published work reveals complicated, coordinated manufacturing capabilities, which imply vigorous organizational competence to have met each new technical demand for a specific manufacturing project. In particular, the gathering and transportation of immense amounts of desert sand, and huge numbers of flint nodules, became vital to the manufacturing processes of sawing, drilling, boring and stone-cutting during the whole of ancient Egyptian civilization.[10]

My extensive experiments, over several decades, with replica and reconstructed tools, point to three naturally-occurring materials, without which the ancient Egyptians could never have developed their intricately devised civilization. I have placed them in my perceived order of importance: flint, desert sand and copper ore. However, a fourth material, the by-product, copper-contaminated powder, is a very early man-made raw material, a hugely critical factor in Egypt's progress towards a sophisticated culture.

There is significant, interconnected technical evidence presented in this thesis to suggest that the ancient Egyptian economy *periodically* expanded in size, organization and diversity throughout the Predynastic and Dynastic Periods, influenced by Dynastic change, complexity and size of state projects, and meagre, or destructive, Nile inundations, but often aided by occasional, inspired inventiveness.

The experimental results suggest that the rulers of ancient Egypt, and increasingly their subordinates, progressively ordered more complicated and elegant artefacts *partly* because craftworkers could modify existing technology to make them, as well as to invent new tools, when required. This in turn created a growing economy affecting many types of people, which required frequent, necessary, systematized changes to work practices that inevitably altered the direction, pace and structure of ancient Egypt's social evolution throughout Egyptian civilization.[11]

Footnotes:

1. Stocks, D.A. 2003b. 'Immutable laws of friction: preparing and fitting stone blocks into the Great Pyramid of Giza', *Antiquity* 77: 573, fig. 1; Stocks, D.A. 2016. 'Scientific evaluation of experiments in Egyptian Archaeology', in Campbell Price, *et al* (eds.), *Mummies, Magic and Medicine in Ancient Egypt: Multidisciplinary Essays for Rosalie David*, Manchester: Manchester University Press, 453-6.
2. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 25.
3. Petrie, W.M.F. 1890. *Kahun, Gurob and Hawara*, London: Kegan Paul, Trench, Trübner, and Co., 34; Petrie, W.M.F. 1917. *Tools and Weapons*, London: British School of Archaeology in Egypt, 23, pl. XXIV, K16-18.
4. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 44-5, figs. 2.28, 2.29.
5. Ibid., 105-9.
6. Stocks, D.A. 2001d. 'Testing ancient Egyptian granite-working methods in Aswan, Upper Egypt', *Antiquity* 75: 89-94.
7. Stocks, D.A. 2002. 'Technical and material interrelationships: implications for social change in ancient Egypt', in W. Wendrich and G. van der Kooij (eds.), *Moving Matters: Ethnoarchaeology in the Near East. Proceedings of the International Seminar held at Cairo, 7-10 December 1998*, Leiden: Research School of Asian, African, and Amerindian Studies (CNWS), Universiteit Leiden, The Netherlands, 115.
8. Stocks, D.A. 1989a. 'Ancient factory mass-production techniques: indications of large-scale stone bead manufacture during the Egyptian New Kingdom Period', *Antiquity* 63: 530, table 3.
9. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 237-8.
10. Stocks, D.A. 2002. 'Technical and material interrelationships: implications for social change in ancient Egypt', in W. Wendrich and G. van der Kooij (eds.), *Moving Matters: Ethnoarchaeology in the Near East. Proceedings of the International Seminar held at Cairo, 7-10 December 1998*, Leiden: Research School of Asian, African, and Amerindian Studies (CNWS), Universiteit Leiden, The Netherlands, 115; Stocks, D.A. 2003a. *Experiments in Egyptian*

Archaeology: Stoneworking Technology in Ancient Egypt, London and New York: Routledge, 74-99, 103-138, 139-178.

11. Stocks, D.A. 2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge, 238-9.

Chapter 15

My rôle in experimental archaeology

My rôle in experimental archaeology developed into three distinctive parts – initial research (taking about 30 years until 1979), publications (from 1986 to present), and public outreach (from 1989 onwards, see below): my comprehensive investigation into ancient Egyptian technology using experimental archaeology was an intensive, extended endeavour.

My researches over such an extensive period have helped to enable experimental archaeology to become a recognized sub-discipline of the field of archaeology. Thus, experimental archaeology is now one of a group of academic tools needed to explain, more accurately, how ancient societies and cultures functioned.

My summarized research contained in the preceding chapters suggests that ancient Egyptian technology - its tools, the materials employed and the relevant processes – contributed to an advanced and highly technical civilization.

How did I assemble the components of my experimental research?

From 1969 I created a wide-ranging research programme into ancient Egyptian tools and technology by assembling the evidence for known tools, and visiting world museum collections to actually see them and to handle the artefacts, if possible. I carried out field studies at various sites in Egypt and, additionally, accumulated the evidence for indicated tools undiscovered by field archaeologists.

As a result of this research, I experimentally manufactured more than two hundred replica and reconstructed tools and artefacts from materials similar to those used in ancient Egypt. The experiments focused on determining the purposes for known ancient tools, in addition to establishing possible functions for indicated ancient tools, and whether some known and indicated tools were also interrelated when employed together for manufacturing artefacts.

I have progressively published the experiments, and their findings, in peer reviewed publications, some of them being originally commissioned by editors of prestigious publications, making the research available to archaeologists working in the field of experimental archaeology, and the field of archaeology in general and, where appropriate, to draw attention to the indicated possibility that particular ancient Egyptian technical abilities, for example their stone drilling technology, were also present in other contemporary civilizations, such as ancient Mesopotamia.

I have disseminated the results by another method, public outreach, seeking to inform interested lay persons about my research and its discoveries. Over the years, I have given eighty invited lectures to various organizations, for example Egypt societies, schools, evening learning centres, and for National Science Week (2001). I have taught ancient Egyptian tools and technology for Manchester University Extra-Mural Courses. I have attended and given lectures to eight conferences, for example *Egyptology in the Present: Experiential and Experimental Methods in Archaeolog*y conference held in Swansea, Wales in 2010, and streamed onto the internet to allow interested persons all over the world to experience the conference lectures and, importantly, the demonstrations of tools, and the technology associated with them, and *Moving Matters: Ethnoarchaeology in the Near East. Proceedings of the International Seminar held at Cairo, 7-10 December 1998*.

Another method to bring my research to people's attention was to create three exhibitions on various aspects of my research, each containing photographs, replica and reconstructed tools, and supporting text: an exhibition at the Department of Archaeology, Faculty of Arts, University of Manchester; an exhibition of large photographs of the research replica and reconstructed tools in action for visitors to see in the Pharaonic Village, Cairo, Egypt, as well as the opportunity to watch demonstrations of over one hundred research tools, permanently donated by me to the Pharaonic Village, in an adjacent area staffed by demonstrators trained by me (see Chapter 5); an exhibition board at Manchester High School for Girls, UK.

I have received eighteen commissions from museums, universities and individuals regarding my experimental research into ancient Egyptian technology. Three examples follow, which illustrate the diversity of these commissions:

In February 2009, Dr. Harriet Hughes of Brighton and Hove Museum, UK commissioned me to make two filmed demonstrations - stone vessel manufacture and single and multiple stone bead drilling techniques - for a short interactive film to be installed in a new Ancient Egypt exhibit gallery.

In April 2013, Dr. Campbell Price, Curator of Egypt and the Sudan, Manchester Museum, University of Manchester, commissioned me to write a 500-word description and manufacturing method for Manchester Museum exhibit 1776, a large Predynastic porphyry bowl, for recording as an audio-and-touch guide to assist visually impaired visitors to the Museum.

In October 2013, Dr. Diane Johnson of The Open University, Milton Keynes, UK, commissioned me to write a technical report, to assist her, regarding the Open University's project to make a replica meteorite iron tubular bead based upon Manchester Museum exhibit MM 5303.

There has been media interest in my experimental research project. The work has appeared in The Independent newspaper[1] and in The Times newspaper,[2] as well as in the pan-Arab *Al-Hayat* newspaper.[3]

I have given four radio interviews for various United Kingdom stations, in addition to an interview for the Central Office of Information, UK Government,[4] for broadcasting to the Near and Middle East, as well as two television interviews, with demonstrations of replica and reconstructed tools, for ITV and BBC local television stations.[5]

Between 1999 and 2010 I was consulted regarding demonstrations of my replica and reconstructed tools, and their associated processes, for fifteen television documentaries, the majority filmed on location in Egypt, and each showing me demonstrating my research tools: where appropriate, brief details of the filmed demonstrated tools are contained in some of the preceding chapters. Some of these documentary demonstrations are available for viewing on the web sites of the History Channel, Discovery Communications - The Science Channel, PBS America Channel, and Channels Four and Five, UK, and, additionally, within the accompanying DVD film made in the Manchester Museum, 2013.

Contribution on the standard of research publications

My publication 14, in this thesis, (2003a. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*) was commissioned by Routledge, an imprint of Taylor and Francis Group Ltd, London, UK. Routledge is a leading 'global publisher of quality academic books, journals and online reference'.[6] The text and illustrations were peer reviewed by three appropriate academics prior to its publication. Routledge published my book because they accepted me as an acknowledged expert in the field of experimental archaeology.

My thesis' publications contain papers published in six *Antiquity* journals (1989a; 1993a; 1997; 1999b; 2001d and 2003b). All of the six draft papers were peer reviewed and forthrightly discussed with me by the editors, who each gave encouragement and advice to improve and revise the content material of a paper submitted for consideration. The 1997 paper was edited by Dr. Christopher Chippindale. Worthy of comment is the manner with which he summarized my 1997 paper's content. Dr. Chippindale's editorial summary, placed immediately after the paper's title, 'Derivation of ancient Egyptian faience core and glaze materials', says:

> *An essential ingredient of the lovely blues in ancient Egyptian materials – faience, glazes and frits – is copper. How did the knowledge of that copper use arise? There is a telling congruence with Egyptian techniques in drilling stone artefacts, and the characteristics of the powder drilled out as waste.*[7]

As an independent experimental archaeologist, this summary indicated to me that my research was being valued by the editor of a respected, renowned worldwide archaeological publication. On a personal level, Dr. Chippindale gave to me an increased confidence and aspiration to continue apace with my experimental research.

Antiquity is a prestigious, important Review of World Archaeology. As such, combined with an unwavering policy of the highest academic rigour, applied to whatever archaeological paper is submitted and accepted for publication, *Antiquity* aided me to make six key parts of my experimental research project accessible to world-wide academics and professional people.

The editors of *Antiquity*, and the editors of other publications in this thesis, accepted my offered articles and papers as an acknowledged expert in the field of experimental archaeology. However, five encyclopedia entries, five book chapters and three journal articles in my publications' list were all commissioned by the editors, who also acknowledged me as an expert in the field of experimental archaeology.

Footnotes:

1. The Independent Newspaper. May 1989. Issue No. 798. Home News, 6. An illustrated article on my experimental research by David Keys, Archaeology Correspondent.
2. The Times Newspaper. July 2002. Issue No. 67503. Illustrated review article by Professor Norman Hammond, Archaeology Correspondent, in Notebook, 32, on my Exhibition and Demonstrations Workshop, The Pharaonic Village, Cairo, Egypt.
   The Times Newspaper. October 2003. Issue No. 67886. Review article on Stocks, D.A. 2003. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London: Routledge, by Professor Norman Hammond, Archaeology Correspondent, in 'The Register', 32, called, 'How the

Egyptians got the edge on fine carving'.

3. Al Hayat Newspaper. June 1989. Issue No. 9741. Illustrated article on my research by M. Aref, Science and Technology Editor.
4. Greater Manchester Radio. May 1989. Interviewed on the Alan Beswick show.
   BBC Radio 2. May 1989. Interviewed on the John Dunn show.
   Central Office of Information, UK Government. May 1989. Interview for broadcast on BBC World Service to the Near and Middle East.
   Greater Manchester Radio. May 2002. Interviewed on morning current affairs programme reference the Demonstrations Workshop, The Pharaonic Village, Cairo.
   Greater Manchester Radio. April 2004. Interviewed on the Alan Beswick morning current affairs programme reference publication of Stocks, D.A. 2003. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*, London and New York: Routledge.
5. Granada Reports, Granada Television. May 1989. Televised interview at home. A demonstration of multiple drilling techniques for stone beads.
   North West Tonight, BBC Television. November 2003. A televised interview at home. Demonstration of the Twist/Reverse Twist Drill for making stone vessels; manufacturing copper chisels; demonstration of the simultaneous multiple drilling techniques for stone beads.
6. Routledge's home page, https://www.routledge.com.
7. Stocks, D.A. 1997. 'Derivation of ancient Egyptian faience core and glaze materials', *Antiquity* 71: 179-82.

Chapter 16

A review of the current state of knowledge and research in the field of experimental archaeology: my contribution to this field

The current state of experimental knowledge and research in archaeology has benefited by developing increasingly focused experiments, particularly in the recent past. In Egyptology, the 1960s and 70s saw experiments in mummification,[1, 2] in the drilling out of stone vessels[3] and in replicating flint tools,[4] further increasing in extent and variety since the early 1980s. In this decade, and later ones, experiments were carried out in diverse areas, such as in drilling stone,[5] in my experiments to indicate mass-production of stone bead perforation,[6] in glass and faience production,[7] in butchery,[8] in textiles[9] and in ritual figurines:[10] these experiments have been valuable, adding to the knowledge of particular areas of archaeological research. Additionally, constructive advice has been made available to experimental archaeologists.[11]

In the more recent past – the 1990s and the 2000s to the present – the scientific analysis of experiments has taken more of a centre-stage position. For example, the use by Ikram[12] of analytical tools for evaluating embalming experiments, such as gas chromatography, mass spectrometry and the scanning electron microscope; the employment by David,[13] Adams,[14] and Johnson[15,16] of X-ray computed tomography (CT) and the scanning electron microscope for the examination of mummy remains, a Gerzean (Nagada II period, c. 3600-3200 BCE) iron bead (Manchester Museum exhibit MM 5303) and its replica made from meteorite iron by Johnson; the use of the Photron Fastcam SA-3 monochrome high-speed camera by Szpakowska,[17] for the examination of the breaking of dropped replica clay figurines, indicates the enthusiasm for utilizing these exciting new ways of experiment analysis. Other techniques include computed radiography (CR) and digital radiography (DR).[18]

Previous experimental research, where helpful, needs to be used, especially if the original experimenter is still able and willing to advise other experimental archaeologists. For example, I was invited to advise Diane Johnson on making an experimental replica meteorite iron tubular bead.[19]

The quality of experimental research in archaeology is, when considering recently published research articles and papers, improving. In particular, the initial research, accomplished competently, and the developed methodology for carrying out experiments, linked to the necessary skills for manufacturing replica and reconstructed tools and artefacts and, appropriately, additionally analysed with relevant scientific tools, indicates that, worldwide, experimental archaeology is becoming more academic, more capable of manufacturing and testing experimental materials and more able to achieve greater experimental accuracy.

However, the considerable thinking ability to visualize in the mind's eye[20] how a reconstructed tool or artefact might have appeared in ancient times will always remain a highly important faculty in creating reconstructed tools, and other artefacts, the testing of them sometimes generating new, unforeseen areas of experimental research.[21]

Whenever possible, experiments should be performed 'on location', where good evidence from field archaeology points to particular tool and artefact manufacturing taking place there. For example, P.T. Nicholson's and C.M. Jackson's[22] significant research experiments at Tell el-Amarna, Upper Egypt into the production of ancient glass and other vitreous materials, have better contributed to our knowledge of these ancient technologies. My experimental drilling and sawing 'on location' in an Aswan granite quarry, with a full-sized reconstructed copper tubular drill, and a full-scale reconstructed copper saw,[23] produced more accurate drilling and sawing data-sets than the smaller, original workshop copper drill-tubes' and saws' data-sets, as did experiments repeated by me in various other locations in Egypt.

Helpful and encouraging to a positive assessment of the current state of knowledge and research in the field of experimental archaeology include themed conferences: the 2010 conference in Swansea, UK – *Egyptology in the Present: Experiential and Experimental Methods in Archaeology* - allowed twenty-three researchers academically, and demonstratively, to present their most recent experiential and experimental research in a variety of archaeological situations.[24]

Currently, knowledge and research in experimental archaeology courses is now being offered to interested students. For example, Exeter University, UK offers an MA Course; Sheffield, UK offers an MSc Course; and the University of Copenhagen also teaches experimental archaeology.

My contribution to experimental archaeology

My contribution to experimental archaeology is summarized in four groups below, based upon the findings headings at the ends of Chapters 2-13:

Group 1 (Chapters 2-5)

Chapter 2 defines what stone hardnesses, and other materials, can effectively be cut with copper, bronze, iron, and flint chisels, punches and scrapers. Each replica copper and bronze test chisel was cast containing measured other constituents, like iron or tin, and the chisels' relative hardnesses established using an accepted mechanical engineering method. In this way, a hardness relationship was established between each replica metallic tool. All chisels' test cutting capabilities for a range of stones, woods and other materials could now be ascertained, including the knapped flint chisels, punches and scrapers.

My cutting results' evaluations led to the establishment of a demarcation line for the stone types able satisfactorily to be cut by copper, bronze and iron tools. Ancient copper and bronze tools, having known, similar content values, can now be given estimated hardness values which, in turn, indicate their ancient cutting abilities. For hard stones, including all igneous ones of hardness Mohs 7, and also for copper or bronze artefacts, flint tools possess the ability to cut, punch and scrape these disparate materials.

Chapter 3's experimental results determined the ability of drillers and sawyers to work all stones using flat-ended, copper tubular drills and flat-edged, copper saws with sand abrasive and, firstly, to demonstrate how the tools were reconstructed, according to the evidence. My experimental drilling and sawing of hard stones, especially igneous stones, produced huge amounts of finely ground, sand-based powders, a significant proportion of them consisting of the copper particles ground off the two tools during their use: the experiments' data-bases record the amounts of raw sand, finely ground, copper-contaminated powders and the quantities of copper lost from the saws and drill-tubes for removing a known quantity of stone.

The experimental results revealed the true economic costs of making important, expensive artefacts, such as stone sarcophagi and stone vessels, as well as the human health costs involved in operating the tools for making them.

Chapter 4's experimental manufacture of a test stone vase, using reconstructed tools indicated in tomb drawings, established the manufacturing times, and the materials consumed, for producing straight-sided and bulbous-shaped stone vessels of both softer and harder stones.

Chapter 5 determined that the waste sand/stone/copper-contaminated powders, a *by-product* material obtained from the experimental tubular drilling and sawing of various stones for stone vessels and other large and small stone artefacts, supplied ancient Egypt's industries with raw materials, which enabled the copper ground off the tools further to be used for making faience, frits and pigment, including a probability that this particulate material was also employed as a fine abrasive for drilling stone beads and for polishing them, together with other stone artefacts, such as granite temple columns.

The experiments suggested that separate ancient tasks for stone drilling and sawing, faience manufacture, bead perforation and stone polishing, involved the following operations: the smelting of copper ores; the manufacture of copper and bronze tools for drilling and sawing stone artefacts with desert sand abrasive; the transference of waste sand/stone/copper particle powders to faience and jewellery-making workshops, and stone polishing locations; the manufacture of faience cores and glazes from powders resulting from drilling and sawing hard limestone, travertine and igneous stones; the firing of the ceramics in a kiln to make the blue or green glazed faience product.

These integrated, complex processes must have created major economic activity in several important areas of technology for thousands of years, commencing in the Predynastic Period of Egypt. My contributed experimental research, in these areas of ancient expertise revealed in Chapters 3-5, has uncovered this raw material and its availability to make artefacts, which has changed our perception of ancient Egypt and, therefore, the field of Egyptology.

Group 2 (Chapters 6, 7)

Experiments in Chapter 6 established how three replica calibrated stone surface accuracy testing tools could direct the ancient masons' accurate fitting of limestone blocks into the Great Pyramid. The experimental findings, combined with the results of testing the flatness, horizontality and verticality of some of the blocks' fitted into the Great Pyramid with the three calibrated replica tools, soundly suggest the ancient methods for constructing the Great Pyramid of Giza.

Chapter 7's experiments demonstrated, by applying the immutable laws of friction, how stone blocks could satisfactorily be moved up and down ramps, in addition to sliding them into position during building work.

Group 3 (Chapters 8, 11)

Chapter 8's experimental work identified an ancient major manufacturing problem – the casting of large objects in metal – and to suggest, using the project furnace's melting capacity, as well as the ancient Egyptians' ability, later in their history, to supply large volumes of air to furnaces by foot-operated bellows, that a cluster of closely located furnaces were needed concurrently to be operated near to a casting location.

Chapter 11's research and experiments revealed that mass-production methods were eventually established in several disparate areas of work in ancient Egypt, increasing the manufacture of artefacts, such as stone beads for jewellery manufacture, for identically cast copper and bronze tools, and for cores to make identical faience objects.

The experimental amethyst bead's threading hole's cutting rate by a single, copper bead-drill, in addition to the reconstructed mass-production simultaneous, multiple, threading holes' cutting rates of the Eighteenth and Nineteenth Dynasty bronze bead drills are recorded, in addition to suggesting the establishment of *workshop* mass-production methods operating in the New Kingdom Period of ancient Egypt, according to the evidence from a drawing in the Theban tomb of Sebekhotep.

Group 4 (Chapters 9, 10, 12, 13)

Chapter 9's experiments established the operating procedure for a reconstructed device that allowed the cutting of thick planks by a single worker. As the tool incorporated a quick-release and quick-tighten facility, sawing proceeded at an even greater rate than previous sawing methods.

Chapter 10's experiments revealed how a replica drill-stock could be fitted with three tools, the copper drill, the fire-stick and the flint drill, or borer, as required by a craftworker, thereby making it a viable, time-saving, interchangeable tool drill-stock.

Chapter 12's research and experiments interpreted an illustration in the Eighteenth Dynasty Vizier Rekhmire's tomb, a tripod anvil for assisting vessel manufacture. The adjustable reconstructed tripod anvil indicated an increased ancient production rate for vessels of metal and of stone.

Chapter 13's experimental manufacture of a reconstructed yarn twisting tool, depicted in the Eighteenth Dynasty tomb of Rekhmire, demonstrated that it could produce twisted yarns accurately and quickly. Further, continued experiments revealed that primary yarns could be twisted together to form stronger strands, the basis for string and rope manufacture.

My experimental research has revealed, and established, how numerous ancient Egyptian tools, processes and industries functioned in Egypt's economy, and my published experiments allow world archaeologists to be aware of my methods and results. It is anticipated that the published experiments, and their associated research findings, will be of future assistance to archaeologists' studies of other ancient civilizations' technologies and economies.

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Publication 1

1989a. ‘Ancient factory mass-production techniques: indications of large-scale stone bead manufacture during the Egyptian New Kingdom Period’, *Antiquity* 63: 526-31.

Ancient factory mass-production techniques: indications of large-scale stone bead manufacture during the Egyptian New Kingdom Period

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Among the craftworkers depicted in Egyptian tomb-painting are drillers of beads about their work. An experimental study of bead-drilling leads to an assessment of the industrial nature of the enterprise.

In certain New Kingdom tombs of the necropolis at Thebes, Upper Egypt, ancient artists painted representations which purport to show craftsmen simultaneously drilling holes in multiple numbers of stone beads; drillers are depicted spinning two, three, four, and sometimes, five drill-rods at the same moment. Most craftsmen, however, are shown drilling three beads together. There are six good examples. In one of the tombs, that of Rekhmire (FIGURE 1a), a single craftsman is shown, whereas in the tomb of Sebekhotep (FIGURE 1b) several bead drillers are depicted. Other scenes are contained in the tombs of Puyemre, Amenhotpe-si-se, Nebamun and Ipuky and Neferrenpet. The tombs date from between 1475 and 1290 BC. Each tomb painting, with the exception of Neferrenpet, is associated with stone beads. As far as may be determined, no other representations of this craft practice have been discovered outside the Theban necropolis, and no multiple bead drilling apparatus has ever been located in Egypt.

It is thought that bow drilling in Egypt originated from the bow and arrow, which developed into the fire drill (Petrie 1917: 59). The bow drill was also utilized for turning tubes of copper for drilling stone (Stocks 1988: 100–67), probably commencing in the late predynastic period, and augers for drilling holes in wood. Tubular drills were never depicted in tomb scenes, but bow-driven augers were (cf. Davies 1943: plates LII, LIII). Small single bow-driven bronze bead drills, from a Dynasty XII (*c.* 1900 BC) site, were discovered by G.A. Reisner (1923: IV–V, 93–4). From FIGURE 1a, several points may be noted.

The estimated length of the arc-shaped bow-shaft is 120 cm with a diameter of 1.5 cm. Its shape is different than other depicted bows, which were shaped like an elbow. The operator is shown holding the extreme end of the bow with his thumb or fingers intertwined with the bow-string, which passes around the lower, thinner drill-rods in turn. The colour of the drill-rods is yellow, and likely to be bronze (Davies 1943: 49). The thicker, upper handles were probably wood (Davies 1925: 63). The three-legged table shows a considerable thickness to the top, and three of the scenes depict different ways of steadying the table (cf. Wreszinski 1923: plate 154; Davies 1925: plate XI; 1943: plate LIV). An example of the three-legged stool is in the British Museum (2481).

After study of these representations, in addition to other evidence (Stocks 1988: 100–213), reconstructions of all parts of the bead drilling apparatus have been manufactured for experimental test and evaluation (Stocks 1988: 214–45). Where possible, similar materials to those known to have been indigenous to Egypt, and in use in the New Kingdom, have been employed for the reconstructions.

Manufacture of experimental artefacts

Artefacts were manufactured as follows:

1 *bow-shaft*

The bow-shaft could have been made from a

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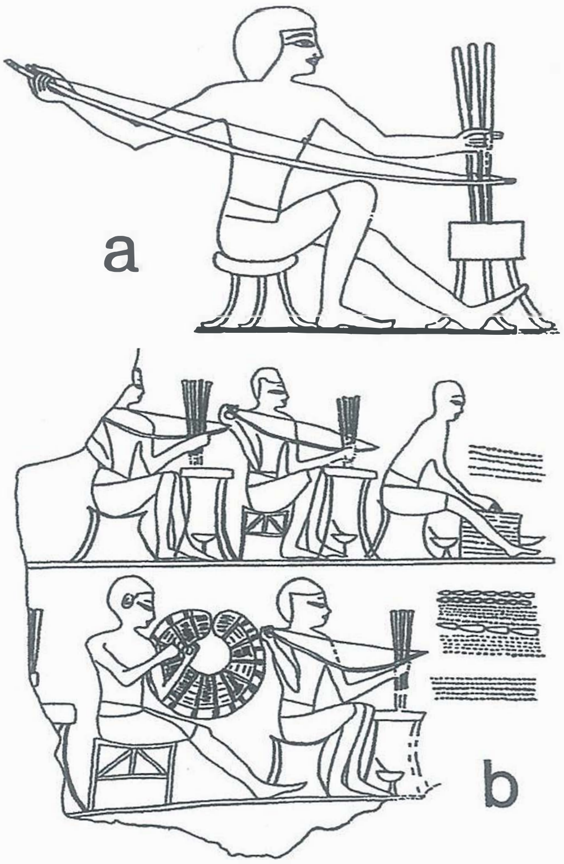

FIGURE 1a. *A craftsman spinning three drill-rods simultaneously. From the tomb of Rekhmire at Thebes. (After Davies 1943: II, plate LIV, courtesy of the Metropolitan Museum of Art.)*
1b. *Several bead drillers using simultaneous multiple bead drilling machines. From the tomb of Sebekhotep. (After British Museum exhibit 920.)*

slim seasoned branch or a bamboo-like reed, for example, *Arundo donax* or *Phragmites communis*.

Although tomb representations of the bow-shaft do not show leaf joints, there are instances of reed blowpipes being depicted without the leaf joints visible (Blackman & Apted 1953: plate XVII). The project bow was manufactured from a 1.5-cm diameter bamboo cane 120 cm long; it was bent into a permanent arc, although tests revealed that a seasoned branch was just as effective. The cane was strung with coarse-fibred string 2 mm diameter, which was probably used at Thebes (cf. BM 43226). The bow-shaft needed a controlled increased resistance to bending and, therefore, the ability to place an adjustable tension upon the string.

2 *drill-rods*
Three bronze drill-rods were cast into vertical open moulds in sand made by a 0.5-cm diameter rod of wood, this being the estimated ancient drill-rod diameter. The average drill-rod length was 15.5 cm, but measurements of represented drill-rods indicate lengths of 20–30 cm. The bottom ends of the rods were finished by grinding on a piece of sandstone. The points measured 2 mm diameter, tapering slightly for a length of 3 mm; this 2-mm dimension applied for drilling tests on calcite and serpentine. Later, for the tests upon hard stone, one point was reduced to 1 mm diameter.

3 *wooden handles*
The handles are similar in length, and mainly taper from top to bottom. It is thought that these ancient handles were carved from tree branches, as they naturally taper during growth. Acting upon this supposition, a set of three handles was manufactured from suitably seasoned tree branches. These were further prepared by burning 1-cm deep holes into the centres of their lower ends. One of the bronze drill-rods, red-hot at its upper end, was utilized for this purpose. This technique ensured that the holes were slightly larger in diameter than the drill-rods. It was found to be of the utmost importance that the drill-rods spun freely in their lubricated bearing holes.

4 *table*
The ancient artist has provided no information regarding the manner with which beads were fixed into the table-top. It is suggested that the table-top could have been hollow. It is thought that this hollow, if it existed, could have been completely filled with pliable clay/mud, similar to mud brick manufacture. Experiments with beads set into clay/mud, which was then allowed to harden naturally, demonstrated that beads may conveniently be set in a line and correctly spaced apart. Also, any bead size or shape can be dealt with in this manner, and may be placed at whatever angle is required for each perforation. Beads may easily be removed without damage after drilling. Further, long convex bi-cone beads (Beck 1927: plates II, III) could be

partially drilled, then reversed for final boring. Other methods may have been in use during ancient times. For example, beads may have been forced into holes bored into the thick top of the wooden table.

Drilling abrasive

The experimental drilling of hard and soft stone by copper tubular drills with dry, coarse quartz sand abrasive has been investigated using reconstructed drills mounted on wooden shafts and driven by bow (Stocks 1988: 100–36). The experiments produced a finely-ground powder, which consisted of finely-ground quartz sand, fragments of the stone itself, and minute particles of copper. The small bowls, depicted in the tomb representations (FIGURE 1b), would have been ideal for containing this type of abrasive mixed with muddy water to form a runny paste, and it is proposed that ancient bead drilling and polishing craftsmen obtained a finely-ground sand/stone/copper by-product material from craftsmen using copper tubes with sand abrasive (Stocks 1988: 127–8).

Experimental simultaneous multiple bead drilling

It was decided to test the equipment in the manner of the tomb of Rekhmire (FIGURE 1a). Three pieces of calcite had already been prepared for drilling by scraping depressions into them by means of a flint scraper (Quibell & Green 1902: 11). This ensured that the drill-rods were correctly centred prior to being spun by the bow. The beads were then set into clay/mud, which had previously been pressed into the top of the drilling table. The calcite beads were set in a line approximately 1.5 cm apart. This measurement is similar to the space between each drill-rod, when held in line, and ready for spinning within its bearing hole in the base of each handle. Trial and error led to the equipment being assembled for use in the following manner:

1 it is suggested that in ancient times the bow-string was securely fastened to the end of the bow-shaft not held by the craftsman; the other end of the string may have possessed a loop which loosely fastened around the bow-shaft where the craftsman's right hand held it. This stratagem would have ensured that, by sliding the loop towards the end of the shaft, tension could be placed on the string as the shaft bent. Conversely, sliding the loop towards the centre of the shaft would slacken the string as the bow-shaft relaxed. This technique was adopted for the experiments. With the string considerably loosened, by using the sliding loop mentioned previously, enough slack was made to allow one turn of the string around each drill-rod. The turns were all in the same direction;
2 the lower ends of the drill-rods were located in their respective bead holes;
3 paste was spooned onto the beads;
4 the handles' bearing holes were all located on the top ends of their respective drill-rods;
5 the left hand gripped the handles in a line. The thumb was in front of the handles, the fingers behind;
6 the right hand now gripped the bow-shaft with the fingers; the string was made to pass behind the thumb, not in front of it (cf. FIGURES 1a, 2). The right hand could be made to slide along the shaft with the thumb hooked under the looped end of the string. The tension induced by these actions ensured that each drill-rod was gripped by the string.

Experiments determined that the right arm could drive the bow forwards until the hand travelled a distance of about 60 cm, or half the length of the bow. In order to keep the bow travelling in a straight line, the right wrist progressively bent away from the operator during the inward stroke and, conversely, towards the operator on the outward stroke. All the drill-rods revolved simultaneously. The experiments determined that the tension imposed by the string on the drill-rods was critical. Should the tension be too great the drill-rods would not turn easily. Conversely, if the tension was too slack the string slipped around the drill-rods without turning them. It was quite noticeable that, whilst the bow was being driven to and fro, the right-hand thumb automatically adjusted the tension on the string to maintain drill-rod revolutions.

Calculations based upon a stroke length of 60 cm, a rod diameter of 0.5 cm, and a stroke rate of 40 per minute show that the number of rotations by each drill-rod to be in the order of 1500 per minute. A stroke rate of 40 per minute was

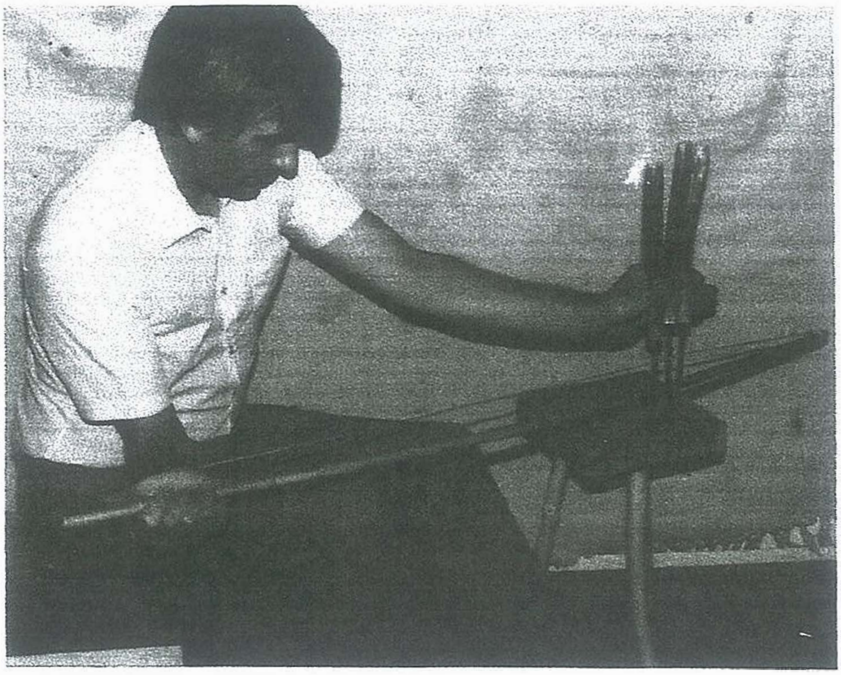

FIGURE 2. *The reconstructed drilling apparatus in use upon specimen calcite beads.*

found to be the optimum frequency necessary to keep up high drill-rod rotations, and also to maintain the drilling action without instability or undue friction to the string. The actions necessary to maintain drilling are not tiring. The weight the left arm naturally places upon the drill-rods is quite sufficient to initiate and continue the drilling procedure.

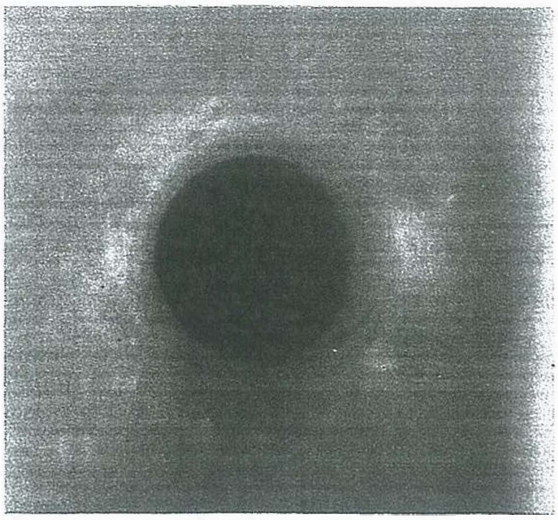

FIGURE 3. *2-mm diameter perforation in calcite drilled by test tapered bronze drill-rod. There are fine horizontal striations visible on the walls.*

The project drill-rods were used in a fully annealed state; this better allowed the tiny quartz fragments in the abrasive to embed themselves into the metal. It was noticeable that the point of the test drill-rod changed into a blunted shape; it did not alter during the tests. The drill point and perforation walls were all striated by the quartz fragments, but these grooves are extremely fine in appearance. Holes inwardly tapered from the bead's surface towards the centre (FIGURE 3). Ancient bead perforations have similar tapers (FIGURE 4). These may be caused by tapered drill points and precessional movement initiated by a bow's to-and-fro action.

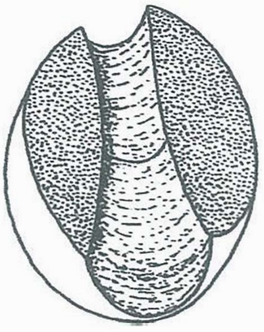

FIGURE 4. *A section of an 8-mm diameter carnelian bead to illustrate ancient joined tapered perforations achieved by drilling from opposite sides. (After Manchester Museum catalogue number 63153).*

Specimen perforation results

bead material	diameter of hole (mm)	depth of hole (mm)	drilling time (mins.)	rod length lost (mm)
calcite	2	5.0	30	<0.05
serpentine	2	1.5	15	0.30
quartz	1	0.5	12	0.20
amethyst	1	0.5	15	0.20

TABLE 1. *Drill-rod point diameters, hole depths, drilling times and drill-rod lengths lost in each material tested.*

bead material	ratio: bronze to stone	rate (cubic mm per hour)
calcite	1:>100	30
serpentine	1:5.0	18
quartz	1:2.5	2
amethyst	1:2.5	2

TABLE 2. *Ratios of bronze drill-rod lengths lost to depths of stone penetration, together with cutting rates in each material tested.*

bead material	diameter of hole (mm)	hole depth (mm)	single rate (mins.)	mass-production rate (mins.) one bead per:
calcite	2	10	60	20
serpentine	2	10	100	33
quartz	1	10	240	80
amethyst	1	10	300	100

TABLE 3. *Indicated mass-production perforation rates per operator (three drill-rods) in calcite, serpentine, quartz and amethyst.*

Conclusions

The experimental work has shown that ancient simultaneous multiple drilling of stone beads was feasible, and perforation must have been the most difficult part of stone bead production processes.

All the evidence examined, archaeological, epigraphic and experimental work, appears to confirm that ancient craftsmen adapted earlier single bead drilling techniques into the simultaneous multiple drilling technology of Dynasties XVIII and XIX. The implication from the representations, particularly that of Sebekhotep (FIGURE 1b), is that factory techniques for mass-producing stone beads were operating in the New Kingdom period at Thebes, and this must have greatly reduced the time, and cost, for bead manufacture.

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The Hjortspring boat reconstructed

JØRGEN JENSEN*

The Hjortspring boat, from south Denmark, is an early case of the successful excavation of a wooden boat, and its more-or-less successful conservation. Sixty years on, further conservation work has given some new observations and a radiocarbon date.

For more than 20 years the early Iron Age Hjortspring Boat, excavated in the 1920s in south Jutland, has been removed from the exhibition at the National Museum in Copenhagen. In the 1960s it was realized that the boat needed total re-conservation; a progressive decomposition of the wood had followed the original conservation technique, which was based on alum (potassium-aluminium sulphate) with added glycerine. The glycerine, however, made the preserved wood hygroscopic, so that it altered with changing humidity and temperature. Measurements of the climate in the exhibition hall did not reveal this because the boat in itself functioned as an air-conditioner. But through the years the alternating content of water in the wood made the alum crystallize, and the crystals gradually broke up the wood. In the mid 1960s the whole Hjortspring find had to be removed from the exhibition and given protracted treatment.

Through the conservation of the Viking ships from Roskilde Fjord, new conservation techniques had been developed. The wood of the Hjortspring boat could now be preserved with polyethylene glycol (PEG). The rescue work was successful, but when done, there were no further economic resources for the continuation of the work. All the wood from the Hjortspring find had to be stored away in the basement of the National Museum for more than 20 years.

In 1985, however, it became possible to continue work through private funding, and in 1988 the boat regained the place which it deserves in a newly-established exhibition hall (FIGURE 1). Many new observations were made during the conservation process, and there are good reasons to draw attention to this unique but neglected find.

The boat

The boat is now displayed on a light steel construction which underlines the main characteristics of the big, plank-built vessel. In spite of much damage caused by peat-digging in the 19th century, the reconstruction of the boat is

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Publication 2

1989b. ‘Indications of ancient Egyptian industrial interdependence: preliminary statement’, *The Manchester Archaeological Bulletin* 4: 21-6.

INDICATIONS OF ANCIENT EGYPTIAN INDUSTRIAL INTERDEPENDENCE

Preliminary Statement

by

Denys Stocks

The ancient Egyptians manufactured many kinds of artefacts which required heavy industrial operations. In particular, two copper engineering tools, of which no trace now exists, were employed with desert sand abrasive to drill and saw large stone objects, for example, sarcophagi. Recent research now suggests that the by-product material of these operations was systematically stored and supplied to other craftsmen for drilling beads, polishing jewellery, statuary, stone vessels and other stone objects, in addition to making faience cores and glazes.

Introduction

Modern industrial society is totally dependent upon many factors for its continued success. There is interdependence between the extraction of raw materials and the machines to excavate them, factory production, and the furnishing of by-products to enable other industries to flourish. One modern by-product is the finely powdered fly-ash left from burning ground-up coal in power stations. This powder, once regarded as a waste material, is now utilized for constructing road embankments and the manufacture of building blocks. There are other such by-products, for example, saw dust, which is mixed with adhesive and compressed to make boards as a substitute for more expensive timber products.

If our industrial society is interdependent and adept at organising itself in the skilled use of by-products from other industrial effort, did ancient civilization achieve any technological interdependence involving the use of by-products for ancillary industries? Recent experimental work (Stocks 1988) strongly suggests that in ancient Egypt there could have been several by-product materials created by the main industrial processes in use during Egyptian civilization. This short paper will look at one of these by-products, which must have been manufactured in considerable quantities.

An indicated ancient Egyptian by-product material

Experimental drilling and sawing of hard and soft stone with copper tubular drills and saws employing dry quartz sand as a cutting abrasive, has produced considerable quantities of a finely-ground (powdered) sand/stone/copper by-product material; two of the stones drilled and sawn were rose granite and limestone (Stocks 1986: 24-9; 1988: 100-43). There is ancient evidence that sand was in use with copper drills and saws (Petrie 1883: 174-5; Reisner 1931: 180; Lucas 1962: 74), but no tubular drills and stone-cutting saws have ever been located. Extensive experiments have proved sand's ability to cut any stone in Egypt. Briefly, the technology of drilling and sawing stone by copper tools and sand abrasive depends upon individual angular sand quartz crystals embedding themselves into the relatively softer copper for a split second as a drill rotates, or a saw moves to and fro; the cutting surfaces of each tool are perfectly flat. During this short period, pressure applied to the drill or saw forces a crystal to score the stone artefact. A groove or striation results from this interaction, and the crystal wears or fragments. These transactions take place with many crystals each second. Crystals not actually cutting grooves, for example, spherical-shaped crystals, or crystals jammed into grooves already cut into the stone, abrade and pit the copper tool. Tiny fragments of copper are absorbed into the powdered product of drilling and sawing.

Experiments determined that in granite, the excavation of 1 cubic cm grinds away 0.33 cubic cm of copper from the tool (ratio of loss of 1 volume unit of copper to excavation of 3 volume units of granite: **weight** of copper lost = 0.33 x 8.94 g = 3 g, where specific gravity of copper is 8.94 g/cubic cm). In limestone, the excavation of 1 cubic cm grinds away 0.0025 cubic cm of copper from the tool (ratio of loss of 1 volume unit of copper to excavation of 400 volume units of limestone: **weight** of copper lost = 0.0025 x 8.94 = 0.022 g).

The powder from working granite by these methods is dark grey in colour, and has the consistency of flour. Most of the powder consists of worn or shattered particles of stone, quartz crystals, copper and accompanying sand contents other than quartz. The particles measure from 0.2mm down to less than 0.5 microns. Much of this powder is comprised of a very fine dust which lies between the measurements of 0.5 and 5 microns (Stocks 1988: 127). In black granite and basalt, the powder is very dark grey, its colour slightly lightened from true black by the sand grains. This particular powder, in addition to rose granite powder, has the appearance and feel of powdered emery. Powder produced from drilling and sawing limestone, however, is almost white, but tinged slightly brown by the colour of the sand. The main difference between the granite and limestone powders is the amount of copper particles each contains. Granite powder contains a considerably greater proportion of copper particles due to the hardness of the stone causing a higher wear rate to the copper tubular drills and saws.

Tests indicated that, on average, the quantity of sand required to excavate 1 cubic cm of granite with a copper tube or saw was approximately 250g. Limestone required approximately 20g of sand to excavate 1 cubic cm of stone. Therefore, in an average sample of granite powder containing 250g of sand, 2.7g of granite (specific gravity of granite = 2.7g/cubic cm) and 3g of copper, the percentage composition is:-

sand = 97.7%; granite = 1.1%; copper = 1.2%

Note: copper has a specific gravity approximately three times that of granite and limestone.

An average sample of limestone powder may contain 20g of sand, 2.6g of limestone (specific gravity of limestone = 2.6g/cubic cm) and 0.022g of copper. The percentage composition is:-

sand = 88.4%; limestone = 11.5%; copper = 0.1%

The percent copper content in granite powder is about 12 times that of the percent copper content in limestone powder.

The powdered by-product has been experimentally used as a runny paste to perforate stone beads (Stocks 1986: 2-7; 1988: 214-45). It is thought that a paste would have been used to perforate and polish ancient beads (cf. painting from tomb of Sebekhotep, exhibit 920, British Museum, where bowls and implements are depicted in association with bead drillers and bead polishing craftsmen). It is also likely that the powder was in ancient use for polishing stone vessels, statuary, obelisks, columns, etc. (Stocks 1988: 127-8, 264). What other purpose may this by-product material have been employed for?

Faience core and glaze materials

Studies of ancient faience cores and glazes have revealed that most faience was made from "...ordinary...raw...dirty...sifted sand..." (Lucas 1962: 155-178, 474-5; Kaczmarczyk and Hedges 1983: 123, 188). The source of the raw materials for Egyptian faience cores and glazes has never been satisfactorily resolved. Acting on a supposition, it was decided to fire:-

a) Test cores manufactured from limestone powder mixed with a little granite powder plus alkali.

b) Glaze from granite powder mixed with a smaller amount of limestone powder plus alkali.

The details of test faience cores and glaze follow:-

1) Two cores each containing by volume:-

Limestone powder	60%
Granite powder	25%
Bicarbonate of soda (alkali)	10%
Clay particles	5%

2) One core containing by volume:-

Limestone powder	55%
Granite powder	30%
Bicarbonate of soda	12%
Clay particles	3%

3) One core containing by volume:-

Limestone powder	65%
Granite powder	20%
Bicarbonate of soda	10%
Clay particles	5%

Each compound was mixed with sufficient water to make a stiff paste, which was moulded into shape and fired at 850 C. After firing the cores had fused and spots of blue could be seen in the matrix. At the time of writing (May 1989), the cores have remained stable for 10 months. There is every indication that cores made entirely from limestone powder would be just as successful. Two of the cores were then coated with a glaze slurry containing by volume, before water:-

Granite powder	44%
Limestone powder	30%
Bicarbonate of soda	20%
Clay particles	6%

Firing took place at 800 C. The originally dark grey (dirty...sifted sand?) glaze turned blue and fused, but the temperature was not high enough to make the glaze flow as glass. It is thought that glaze made from a higher concentration of granite powder would have fired a deeper blue and that a slightly higher temperature would have vitrified the glaze. The limestone powder may be a necessary ingredient to the glaze mixture as this powder increases the amount of lime present in the compound, although some lime will be in the sand (Lucas 1962: 481). Further experiments need to be completed in this direction.

Conclusions

The experiments to date indicate that the powdered by-product material, which **must** be created by drilling and sawing hard and soft stone with copper tools and coarse quartz and abrasive, has the constituents for faience core and glaze base materials. X-Ray Fluorescence and atomic absorption analyses of some ancient Egyptian faience body (core) and glaze material by Kaczmarczyk and Hedges (1983: 58, 185) suggest that the experimentally obtained copper content in the powder could be in the right order of magnitude. Of course, the contents of anciently produced powders could be expected to vary in the amount of copper, sand, alkali and other substances contained within them. In particular, the copper in the tools would contain different values and types of constituent materials. Also, sand from different locations in Egypt would cause variations to the composition of by-product powders.

The foregoing experimental work suggests that ancient Egyptian faience craftsmen obtained their main raw material from stone drillers and sawyers as a by-product, rather than specially manufacturing it. Much time and expense would, therefore, have been saved. A measure of industrial interdependence may be inferred by these proposed interactions occurring at different levels of ancient industrial society.

Acknowledgements

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Making stone vessels in ancient Mesopotamia and Egypt

DENYS A. STOCKS*

How were the fine stone jars and vessels of ancient Egypt and Mesopotamia made? An experimental test of materials and techniques explores the methods of early drilling.

Similarities between the Uruk and Jemdet Nasr periods of Mesopotamia (*c.* 3600–2900 BC) and the Gerzean and early dynastic periods of Egypt (*c.* 3500–2900 BC) include cylinder seals, the recessed panelled façade design in architecture, the use of pictographs, decorative art and the shapes of stone vessels. And craftsmen from Mesopotamia and Egypt necessarily developed similar tools and techniques for manufacturing stone vessels. In order to explore these similarities, I investigated the use of a specialized Egyptian tool in making a limestone vase.

It is generally thought that the cold beating, or forging, of truly smelted and cast copper into tools and other artefacts first occurred in Egypt around 3500 BC (Hoffman 1980: 207), castings being made in rudimentary open moulds at this period (Petrie 1917: 6). Cold-forged, cast copper tools were also manufactured in Mesopotamia (Moorey 1985: 40–46). The technique of beating copper into sheets must have existed in both Egypt and Mesopotamia, where vessels of this metal were found at Ur by Sir Leonard Woolley (Woolley 1955: 30–31). Sheet copper is essential to the making of copper tubes, indispensable tools for drilling out stone vessels. It is likely that rolling copper sheet into tubes imitated nature's own architecture – that of hollow reeds. The direct casting of copper into open, tubular-shaped moulds may also have been adopted by both civilizations.

Stone vessel manufacturing technology

In Mesopotamia, and Egypt, copper tubular drills were used for the initial hollowing of the interiors of vases and jars made from hard and soft stone (Woolley 1934: 380; Moorey 1985: 51; Reisner 1931: 180; Lucas 1962: 74). Striations are clearly visible on the inside walls of vessels, caused by the abrasive material employed with the drills. Although the stone-cutting, copper tubular drill has never been located, it would have been directly driven by a shaft of wood driven firmly into the top end (FIGURE 1a) and rotated by a bow-string (with the top of the shaft in a stone bearing-cap), or twisted clockwise, and anti-clockwise by wrist action. It is unlikely that shafts were rolled between the palms.

Subsequently, Mesopotamian and Egyptian bulbous vessels – those considerably wider inside than at the mouth – were further hollowed by grinding with another tool, a stone borer of elongated form. The mid-point of its long axis was made to narrow equally from both sides. Seen from above, the borer assumes the shape of a figure-of-eight,

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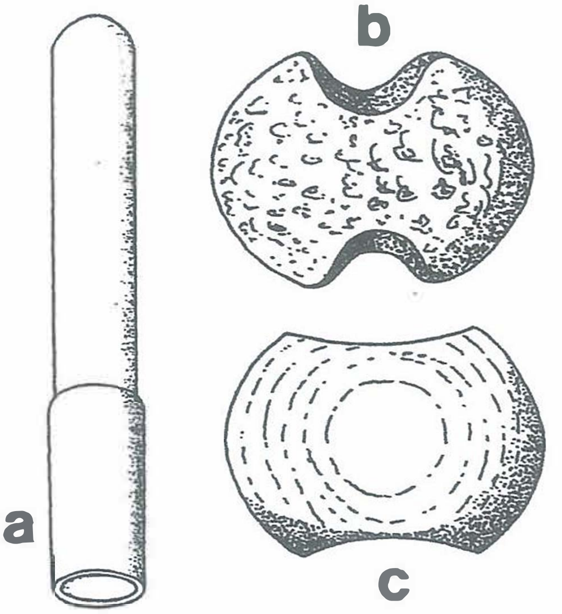

FIGURE 1a. *A copper drill-tube force-fitted to a wooden shaft.*

b. *An Egyptian figure-of-eight shaped stone borer from Hierakonpolis. (After Quibell and Green 1902: plate LXII, 6.)*

c. *A Mesopotamian figure-of-eight shaped stone borer. (After Woolley 1955: figure 15b.)*

enabling a forked shaft to engage with the waist. The top is normally flat, the bottom curved. In Egypt, this particular borer has been discovered at Hierakonpolis, a site associated with late predynastic and early dynastic stone vessel production (Quibell & Green 1902: plate LXII, 6) (FIGURE 1b); Mesopotamian figure-of-eight shaped stone borers were discovered by Woolley at Ur (Woolley 1955: 75, figure 15b) (FIGURE 1c). Circular borers were used to grind stone bowls whose interior was no wider than the mouth. A stone borer in the British Museum (BM 124498 from Ur), curved underneath and flat on top, has a piece cut out from each side of its upper surface, also for retaining a forked shaft. At Ur, stone borers were common in the Uruk and Jemdet Nasr periods, and Woolley thought that the constricted parts of these stone borers were engaged by a forked wooden shaft *driven by a bow* (Woolley 1955: 14) (FIGURE 2). Borers made from diorite are common to Mesopotamia and Egypt; other stones utilized in Egypt included chert, sandstone and limestone.

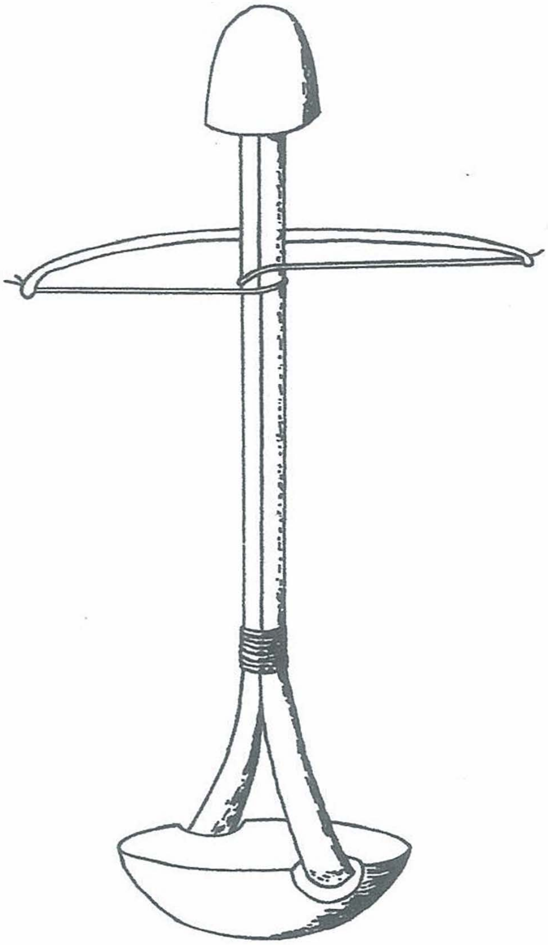

FIGURE 2. *Sir Leonard Woolley's suggested method by which ancient Mesopotamian craftsmen revolved their stone borers for hollowing stone vessels. (After Woolley 1955: figure 5.)*

Striations on Mesopotamian vessels, and the bottom surfaces of stone borers, are similar to striations seen on their Egyptian counterparts – generally 0.25 mm wide and deep. Archaeological (e.g. BM 124498 borer from Ur; Petrie 1883: plate XIV, 7, 8; 1884: 90; Petrie Collection alabaster vase UC 18071) and my recent experimental evidence (Stocks 1988: 111–36) strongly indicate that stone borers, and copper tubes, were both employed with quartz sand abrasive.

The copper tubular drill, rotated with sand abrasive, produces a cylindrical slot round a central core, which is removed to make the full-sized hole. Stone borers, in particular the figure-of-eight shape, were mainly used to enlarge holes already made by a tubular drill. No copper tubes for drilling stone have ever been discovered in Egypt or Mesopotamia; tubes wear down during use, and the short stubs left would have been melted down as scrap. Neither the forked wooden shafts nor the tools that drove them have been discovered. However, they are illustrated in a number of Egyptian tombs constructed between Dynasties V and XXVI; there are no known representations from Mesopotamia.

In these Egyptian illustrations, the vessel obscures the lower, working end of the tool's shaft. However, during Old Kingdom times the ideogram used in words for 'craft', 'art' and other related words depicts a *forked, central shaft* with two weights (Gardiner 1957: 519, sign U25; Murray 1905: I, plate XXXIX, 65) (FIGURE 3a); by the New Kingdom, this ideogram had changed to a forked shaft *lashed* to a *central* shaft with one circular weight (Gardiner 1957: 518, sign U24; Davies 1943: II, plate LIV) (FIGURE 3b). From Dynasty V onwards, a forked shaft was secured to the central shaft of a tool, as seen on a representation from a Dynasty V tomb at Saqqara (Cairo Museum JE39866) and a painted Dynasty XII representation (Fitzwilliam Museum E55.1914 limestone fragment from Lahun).

The Old Kingdom tool consisted of a straight wooden shaft, inclined at an obtuse angle near the top and tapered to a curved, blunt point; it was probably manufactured from a suitable tree branch. Two weights were fastened immediately under the inclined and tapered top part (see FIGURE 3a) to place a load upon a drill-tube or stone borer.

The tool for preliminary drilling operations would have had a copper tube force-fitted on its central shaft (FIGURE 4): some tomb illustrations may display a *central* shaft fitted with a tube for drilling purposes, particularly for wide-mouthed vessels; an unfinished porphyry vase (Cairo Museum JE18758) was drilled with eight adjacent holes to excavate the central mass. It is likely that the drilling tool did not change in form, except for the manner in which it was weighted; a tubular drill would not have damaged its wooden shaft during use, and new tubes could be fitted to the same shaft time and time again.

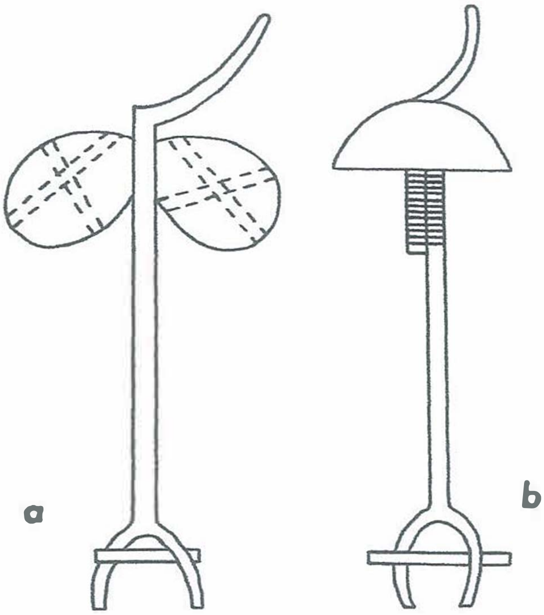

FIGURE 3a. *An Old Kingdom representation of a forked shaft engaged with a stone borer. The tool is weighted with two stones. (After Gardiner 1957: 519, sign U25; Murray 1905: I, plate XXXIX, 65.)*

b. *A New Kingdom representation of a forked shaft, engaged with a stone borer, lashed to a central shaft. The tool is weighted with a single, circular stone. (After Gardiner 1957: 518, sign U24; Davies 1943: II, plate LIV.)*

The ideogram shows only the visually interesting and informative view of the forked shaft and borer, rather than a tube (*cf.* FIGURES 3 & 4).

The tool was adapted for its secondary role, that of a boring implement, by lashing a forked shaft to the central shaft (see FIGURE 3b) to engage with figure-of-eight and circular-shaped borers (FIGURE 5). Another type of stone borer – an inverted truncated cone with two slots cut opposite each other in the upper, horizontal surface – was employed to shape a vessel's mouth (uncatalogued cone, Petrie Collection, University College, London). Crescent-shaped flints, also engaged by forked shafts, were used exclusively for cutting soft stone, for example, gypsum, without sand abrasive (Caton-Thompson & Gardner 1934: 105, 130). In extended use, the forks of reconstructed tools showed wear (Stocks 1988: 168–213). A worn-out forked shaft could be replaced by lashing a new one to the

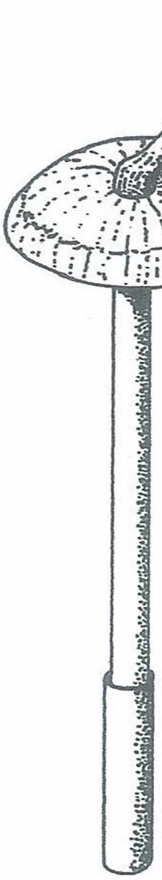

FIGURE 4. *A proposed drilling version of the tool, which has a copper tube force-fitted to its central shaft. This illustration follows the New Kingdom Period upper tool design.*

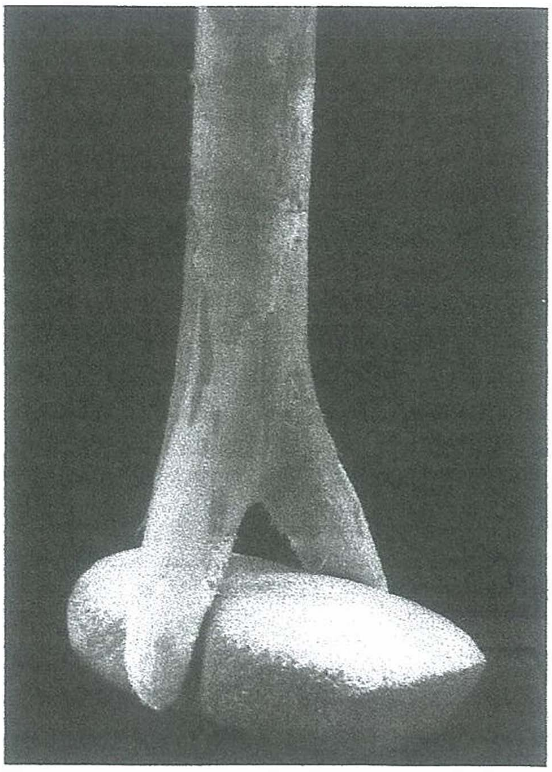

FIGURE 5. *A reconstructed forked wooden shaft, engaged with a figure-of-eight shaped stone borer.*

central shaft, much as a drill-bit is replaced on a modern electric drill. As the destruction of a forked *central* shaft would render the whole tool useless, the tool may have evolved from this original configuration.

The Twist/Reverse Twist Drill (TRTD)

Some copper drill-tubes were driven by bows, e.g. in sarcophagus manufacture in Egypt (Stocks 1988: 114–15, 144–67), but the difficulties of making stone vases with thin walls excluded this technique. I found that the mechanical stresses imposed on thin stone walls by precessional forces in bow-drilling breaks the vessel. Also, the backward-and-forward movement of a bow causes sand trapped outside the tube to enlarge the internal hole out towards the external wall of the vessel, particularly in soft stone. Drill cores produced by bow-driven tubes are tapered (Petrie 1883: plate XIV, 7), which is at variance with the archaeological evidence for stone vessel drilling. An uncatalogued Old Kingdom alabaster vase in the Petrie Collection still retains its parallel-sided core in a hole made by a tubular drill.

I found it best to twist the tool first clockwise, by approximately 90°, and then anti-clockwise to its starting position. One hand grips the inclined and tapered top part, or handle; the other hand grips the central shaft, just below the weights. The curved handle fits the semi-clenched hand perfectly, and must have been chosen and carved for this purpose. In using a figure-of-eight stone borer, the craftsman must periodically change the position of his hands, in order to cut evenly around the whole circumference of a vessel. The twist/reverse twist motion produces a core with parallel sides (FIGURE 6). I have named this tool the Twist/Reverse

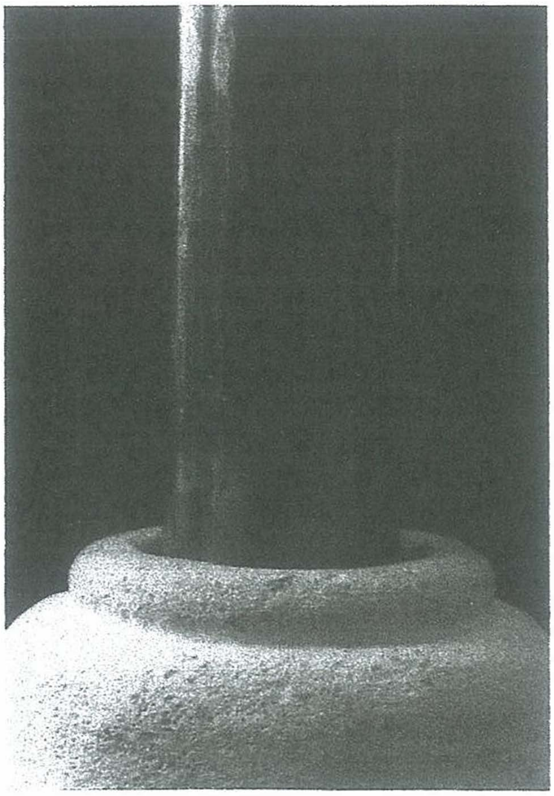

FIGURE 6. *A reconstructed copper drill-tube, shown drilling into the experimental limestone vase.*

Twist Drill, or TRTD (Stocks 1988: 178), calling it a 'drill' even though its other function was boring.

The use of figure-of-eight shaped stone borers of different dimensions allowed gradually changing internal diameters to be ground, and the initial process of undercutting vessel shoulders. The stone borer, when employed with sand abrasive, gives so much resistance that I found it could not be rotated by a bow (as suggested by Woolley).

Experiments with stone borers

In Mesopotamia, only the stone borer has survived to indicate how Mesopotamian craftsmen made stone vessels. The figure-of-eight borer, common to both Egypt and Mesopotamia, is crucial evidence. It is only by using the Egyptian sources, and by experiment, that Mesopotamian stone vessel manufacturing techniques can be assessed.

Figure-of-eight and circular borers were tested for rotation by a bow. The figure-of-eight shaped borer usually touches a worked surface in two distinct places, either side of the forked shaft, whereas a circular borer engages with the whole of its lower surface. *Dry* sand abrasive was employed, as previous experience with copper tubes and stone borers (Stocks 1988: 124–32) has determined that *wet* sand abrasive is not efficient. The essence of drilling and boring with sand abrasive, which contains relatively large quartz crystals, is the continual replacement of worn crystals by fresh, angular ones at the cutting face. Wet sand, or wet sand drying-out, prevents this. Copper tubes can drill stone, even granite, because individual quartz crystals, which are mainly angular in shape, embed themselves into the softer copper for a fraction of a second and are swept around the stone's surface. (I found that a pressure of 1 kg/cm^2 upon a drill-tube's cutting face is optimum.) Stone borers also engage quartz crystals, but not so well.

Very wet, or fluid, sand will interchange, but is unsuitable for other reasons. The sand, when ground, turns into a fine powder, with the texture of flour. This powder packs inside a tubular drill and, even when perfectly dry, sticks together in one mass and remains inside the tube when it is removed from a hole. In this way, the powder from dry sand can be withdrawn from deep, tubular holes drilled into a sarcophagus (essentially a giant stone vessel), whereas wet powder cannot. Egyptian and Mesopotamian craftsmen must have discovered these properties of sand for themselves.

After experimenting with different powders obtained from drilling both hard and soft stone by copper tubes, I propose that ancient craftsmen employed these by-products for drilling stone beads, polishing stone artefacts and creating faience cores and glazes (Stocks 1988: 127–8, 235, 261–4; 1989a: 528; 1989b: 21–6). A stiff paste can be made by adding sodium bicarbonate (natron in ancient times) and water to the powder obtained from drilling soft stone – limestone or calcite (Egyptian alabaster). Moulded or modelled into any shape and fired at 850°C, it becomes a stable, hard, whitish material, speckled with blue spots from particles of copper worn off the drill-tube. Glazed with a runny paste,

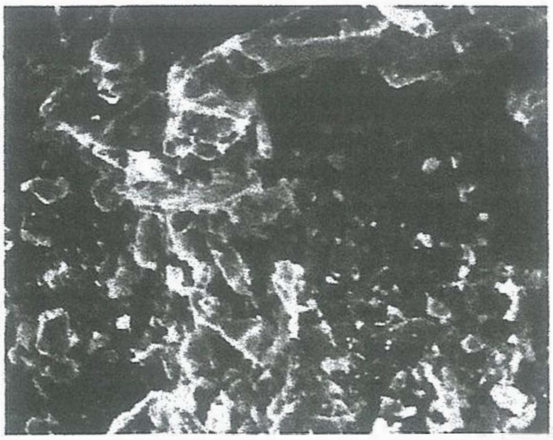

FIGURE 7. *SEM photo of the powdered by-product obtained from drilling rose granite by copper drill-tube and quartz sand. There are many quartz particles lying within the size range of 0.5–5 microns. Scale: 1 cm = 3 µm. (Photo by Barry Oswald, courtesy of Max Lawton and the Department of Pathological Sciences, University of Manchester.)*

made with powder derived from drilling hard stone, for example, rose granite and diorite, and fired again at 800°C, turned the glaze blue. These core and glaze materials are similar to Egyptian faience in appearance. A scanning electron micrograph (SEM) shows that the powdered material contains many particles within the size range of 0.5–5 microns (FIGURE 7), particularly in hard stone powder. Breathing these fine particles causes lung damage to craftsmen (Stocks 1988: 127, 204–5; Curry *et al*. 1986: 58–9, figure 2).

Each test borer was admitted into a previously prepared hole, which imitated the interior of a partly bored vessel (Stocks 1988: 189). A forked shaft was engaged with each borer. A stone bearing fitted the top of the shaft, turned by a bow. The figure-of-eight borer jammed in the hole and caused the bow-string to slip on the shaft. The reason was the result of an out-of-balance centrifugal force acting upon the end of the borer swinging away from the operator. Similar jamming occurred with the circular borer. Even if a borer could be rotated by a bow, sand-induced friction is so high that constantly to overcome it creates unacceptable stresses. The experiments do not support the driving of Mesopotamian borers by bow-driven forked shafts.

Experimental manufacture of a stone vessel

In order to test whether the TRTD could be used to make a stone vessel, a small, barrel-shaped vase (FIGURE 8) was first shaped from soft limestone by copper chisels and adzes, flint punches, chisels and scrapers and sandstone rubbers. It was excavated by two copper tubes, and stone borers (Stocks 1988: 192–212). After shaping, the vase was separately drilled by each tube, one within the other, so as to weaken the core. The eyes in some ancient statuary were made this way, and a tubular *core* that was formed by two tubular drills employed in this fashion was found by W.M.F. Petrie (Petrie 1917: plate LII, 61). The drills were located by chipping and scraping circular grooves that matched each drill's diameter. (An uncatalogued alabaster vessel in the Petrie Collection has a similar groove in its top surface.) I used flint punches,

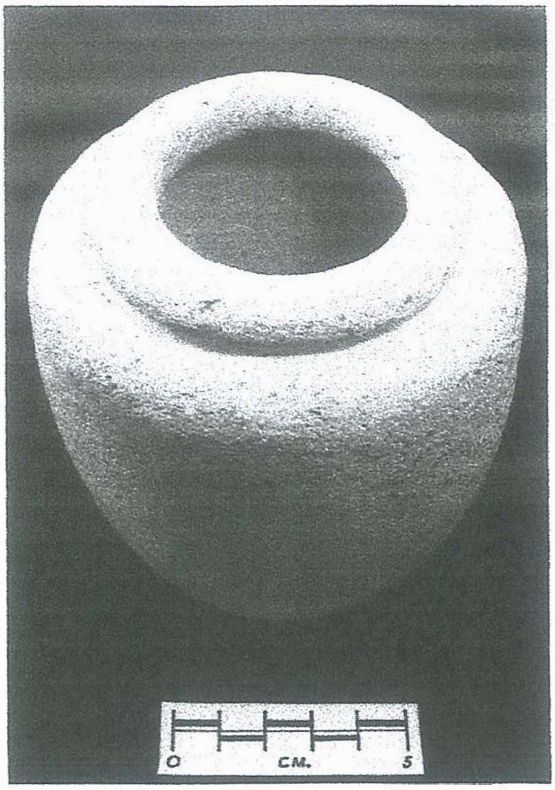

FIGURE 8. *The finished experimental limestone vase. It is 10.7 cm tall and 10.0 cm in diameter. The vase took 22 hours 35 minutes to complete all exterior shaping and interior tubular drilling and stone boring operations.*

chisels and scrapers to create these grooves, and the tools were also found to be effective for granite and diorite. Ancient vessels and hieroglyphs in hard stone were probably shaped and cut by these types of flint tools (Stocks 1988: 246–73).

The drilling took five hours to complete. As soon as a core filled the hollow drill, it was carefully broken off by copper chisel and mallet; this technology allowed ancient drill-tubes to reach to the bottom of deep vessels, and explains why TRTD stone weights were placed high up the shaft. Boring the hole to match the bulbous exterior, by figure-of-eight stone borers, occupied another 10 hours. At any particular point of enlargement, a borer that was slightly longer than the existing internal diameter was selected for use. A borer entered the vessel vertically, and was then turned horizontal; sand was poured into the vase, level with the borer. A forked shaft could now be engaged with the borer. It took an hour to undercut the vase's shoulders by hand-held, hook-shaped flint scrapers, and hook-shaped stone borers, used with sand abrasive.

Tests to drill rose granite and diorite, by a copper tube, showed that these stones took 15 times longer to drill than limestone (Stocks 1988: 212, 340). A granite, barrel-shaped vessel, of similar dimensions to the limestone vase, would take me 75 hours to excavate by drill-tube, although experienced ancient craftsmen would have bettered my cutting rates in both stones. Some test results, which record ratios of copper lost from drill-tubes to excavation depths in stone, and excavation rates, were obtained from drilling granite, diorite, calcite and soft limestone by bow-driven and twist/reverse twist driven copper tubes (TABLE 1).

material	ratio: copper to stone	bow-driven rate (cubic cm per hour)	twist/reverse twist rate (cubic cm per hour)
granite	1:3	2	0.4
diorite	1:3	2	0.4
calcite	1:>100	30	6
limestone	1:>100	30	6

TABLE 1. *Specimen drilling results. Ratios of copper drill-tube lengths lost to depths of stone penetration, together with cutting rates in each material tested. The same tube was used for all tests. In any particular stone, the cutting rates are similar for all diameter tubular drills capable of being driven by craftsmen; larger diameter drills are necessarily revolved more slowly than smaller diameter drills, due to increased inertia and friction. The table shows that twist/reverse twist drilling is five times slower than bow-drilling.*

Conclusions

It is apparent that ancient Mesopotamian and Egyptian stone vessel craftsmen must have adopted the twist/reverse twist manner of driving their tubular drills and stone borers.

Egyptian representations of the tool show its extreme simplicity of form; nowhere in Egyptian representations of stone vessel production does the ancient artist ever display a stone borer being driven by a bow. Tomb artists never showed a tubular drill being driven by a bow, although the use of bow-driven tubes must have been well known. The experiments demonstrate that the twist/reverse twist technique provided the only satisfactory method *any* ancient stone vessel craftsman could have employed for driving tubular drills and stone borers. The figure-of-eight borer can only be driven with the leverage and control of the Twist/Reverse Twist Drill, and the finding of such borers in Mesopotamia indicates the use of some form of this tool.

Acknowledgement. I am indebted to Peter Clayton for reading a preliminary manuscript and suggesting some useful amendments to the text. However, the ideas expressed here are entirely the responsibility of the author.

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Spondylus shell ornaments from late Neolithic Dimini, Greece: specialized manufacture or unequal accumulation?

PAUL HALSTEAD*

Rings and buttons and beads cut from the marine shell, Spondylus gaederopus, *are among the most distinctive exchange items of Neolithic Europe. From sources on the coast of the Mediterranean, these highly valued objects were widely distributed across central Europe. A re-examination of the nature and contexts of shell objects and manufacturing waste at Dimini, a key late Neolithic site on the coast of northern Greece, explores their social role within a* Spondylus-*working community.*

Dimini and its society

The status of Dimini as a chronological type-site for the Greek Neolithic has diminished in recent years: the 'Classic Dimini' ceramic assemblage, probably dating to the early 5th millennium BC (Theochares 1973: 119; Weisshaar 1989: 139), now defines only the last of four or five subdivisions of the Late Neolithic of eastern Thessaly. Dimini provides a unique insight into late Neolithic society, however, because of the extensive scale of excavation at the site. Excavation at the beginning of the century revealed a late Neolithic settlement covering *c.* 1 hectare and consisting of a series of concentric circuit walls around a 'central court' (Tsountas 1908). Re-excavation in the 1970s demonstrated that the circuit walls (previously interpreted as defensive) divide the settlement into 'domestic areas', each containing a few buildings and a range of storage and cooking facilities (Hourmouziadis 1979). The central

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TECHNOLOGY AND THE REED

by

Denys A. Stocks

In ancient Egypt, people were influenced by plants growing around them. For example, plant shapes were copied in stone for architectural purposes, and the papyrus plant was used for the manufacture of paper.

This article looks at how the common reed (Phragmites communis) was used by predynastic craftsmen as a tubular drill for excavating stone, and investigates its efficiency as a drilling tool. Subsequently, the reed's tubular shape was copied in copper, which not only served as a stone cutting drill, but was adapted for use in other areas of Egyptian society. After modification by the craftsman, the reed also gave its shape to the fundamental design of another important ancient tool, that of the furnace blowpipe. Comparisons between reed and copper tubular drills' performance on stone are stated.

Introduction

There is considerable evidence that ancient Egyptian craftsmen copied plant shapes when designing artefacts. For example, ancient Egyptian builders copied the flower of the lotus plant , in bud or fully open, and the leaves of palm trees when creating stone columns.

It is also likely that the craftsman copied the tubular shape of the common reed (Phragmites communis) in copper after 3500 B.C., as the casting of this metal became fully established after this date. Prior to 3500 B.C., the reed itself was in use as a tool for drilling stone, by revolving it upon sand abrasive. [1] The reed was also used for blowing air into furnaces after modification by the craftsman, either as a simple blowpipe or as part of a bellows system.

Reed construction

The slender , straight stem of the reed, a member of the grass family of plants, is hollow along its length, except at the frequent leaf joints which have internal partitions. The common reed usually grows in marshy conditions, where it can attain 5 metres in height; in dry places, it is much shorter.[2] Reeds grew along the river Nile in great abundance in ancient Egypt. Large reeds have a diameter of several centimetres.

The reed as a drill-tube

Before the advent of copper drill-tubes in the Naqada II period (3500-3150 B.C.), craftsmen probably employed a reed tubular drill, in use with sand as an abrasive,[3] for drilling out the interiors of stone vessels. This tube could have been rotated between the hands, twisted by wrist action or driven by a bow (Figure 1). Reed drills will efficiently cut limestone and calcite (Egyptian alabaster), but not hard stones, such as granite and porphyry.[4] Prior to the introduction of copper drill-tubes, hand-held stone borers and sand abrasive were in use for excavating <u>hard</u> stone vessels.

The tubular drill produces a tubular-shaped slot, which surrounds a central core; this technology allows the removal of a small amount of stone by drilling, but achieves the full-sized hole on removal of the core. The use of the tubular drill is an efficient way of removing stone. Sand crystals become embedded in the end-face of the tube, while it is revolved under pressure, and the crystals score the surface of the stone. As the hole deepens, the stone core occupies the space in the tube. At intervals, the core needs to be broken off, and this action allows the drill further to penetrate into the stone.

Experimental tests, which at first used tubular drills of bamboo, a reed-like member of the grasses, were made upon the following stones: soft limestone, hard limestone, red sandstone, calcite, hard sandstone (coarse-grained) and blue granite (close-grained). The bamboo drill-tubes were intended to represent reed drill-tubes; bamboo did not grow in ancient Egypt. The common reed's construction, and hardness of its woody culm (stem), closely resembles bamboo cane, and I felt that a fair assessment of the common reed, as a tube for drilling stone, could be derived from the experiments. The results were confirmed with reed tubes at a later date.[5]

Each test utilized a 1cm diameter hollow bamboo cane possessing 2mm thick walls. The cane was rounded at the top, for the stone bearing cap, and driven by a bow. A load of lkg/cm^2 was applied upon the cane. The drill-tubes were tested with <u>dry</u> and <u>wet</u> sand abrasive. Overcutting of the holes, due to the motion imposed by the bow, was allowed for when calculating the cutting rates for each drill-tube. Therefore, the <u>volumes</u> of bamboo worn off the drill-tube to excavated stone were used to obtain a ratio between the two materials, rather than using linear measurements of the tube and hole.

TABLE 1. Specimen drilling results

(a) by dry sand abrasive

Stone	Ratio: bamboo: stone	Excavation rate: cm^3/hr
soft limestone	1: 3	12
hard limestone	1: 2	8
red sandstone	1: 3	12
calcite	1: 2	8

(b) by wet sand abrasive

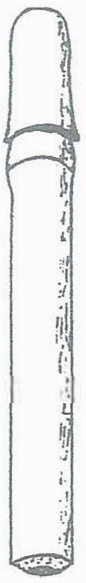
soft limestone	1: 1.5	12
red limestone	2: 1	4
red sandstone	1: 1.5	12
calcite	2: 1	4

Dry sand abrasive caused some splintering to the tube, and the culm spread outwards. However the drill retained its tubular shape and effectively drilled all four stones.

The drill-tube used with wet sand abrasive soon softened and spread outwards and inwards, thus filling the originally hollow interior with soft culm. The tube lost its hollow structure and assumed the shape of a solid stalk. Despite this alteration to the tube's configuration, it performed useful work upon soft limestone and red sandstone, but performed poorly upon hard limestone and calcite. However, because the drill had assumed the shape of a solid stalk, instead of a tube, penetration into soft limestone and red sandstone was slowed down, even though the volumetric rate of excavation remained similar to that of the tube in use with dry sand. The use of bamboo tubes upon hard sandstone and granite, utilising wet or dry sand abrasive, so badly damaged them that no cutting was achieved in these stones.

The reed as a pattern

After the introduction of cast copper the stone vessel craftsman was able to imitate the hollow reed by beating thick sheets of cast copper into thin sheets and rolling them around wooden, cylindrical formers; larger diameter copper tubes may have been directly cast by creating vertical, tubular-shaped moulds in damp sand, initially made by a reed tube acting as a pattern. Later, the wooden pattern and core method of manufacturing cast tubes could have been introduced. A solid cylinder of wood, the pattern, is pushed vertically into damp sand, and then withdrawn. A slightly smaller, cylindrical, dried mud core is then centrally positioned into the hole left by the pattern. Molten copper fills the tubular space surrounding the core. The core is broken out of the casting after cooling.



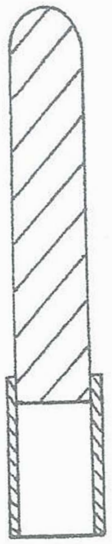
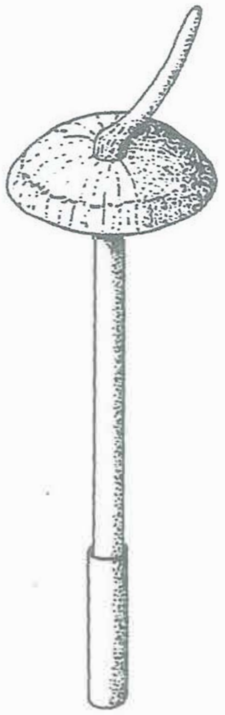


FIGURE 1. (Left). A reconstructed reed tubular drill.
FIGURE 2. (Right). Cross-section of a copper tubular drill mounted on a wooden shaft.



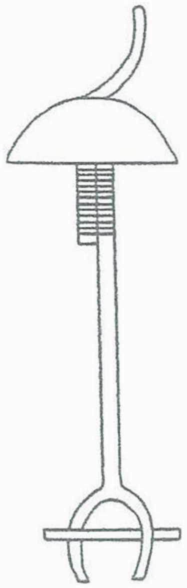


FIGURE 3. (Left). Proposed manner in which an ancient TRTD was fitted with a copper tubular drill. From the 12th dynasty, the TRTD was fitted with a single, central stone weight.
FIGURE 4. (Right). TRTD with lashed on forked shaft for driving stone borers. Ancient artists depicted the figure-of-eight shaped borer in side elevation. Its true shape can only be seen from the top.

Copies of reed tubes made from sheet or cast copper gave four immediate advantages. Firstly, tubes can be manufactured to reasonably accurate diameters, lengths and uniform wall thicknesses. Secondly, copper tubes made from beaten copper sheet have thinner walls, and this means that less stone needs to be removed from a hole. Thirdly, copper drills can excavate hard stones, for example, granite, diorite and porphyry, in addition to softer stones and, fourthly, copper drills wear out much more slowly than reed drills (see Table 2, below). A wooden shaft was then forcibly driven, part-way, into the tubular drill (Figure 2); this allowed either the drill to be rotated by a bow, the upper part of the shaft turning in a hand-held, stone bearing cap, or fitted to a stone vessel drilling tool called the Twist/Reverse Twist Drill (TRTD).[6]

The TRTD was brought into use during the Naqada II (early Gerzean) period, specifically for stone vessel production.[7] The development of this tool enabled craftsmen to drive a copper tubular drill without any lateral pressures , a drawback of bow-drilling.[8] The TRTD was operated by continually twisting the tool, by wrist action, clockwise and then anticlockwise. After a simple adaptation, the TRTD could be utilised for the second part of stone vessel excavation processes, that of stone boring the vessel to its final, internal configuration.

The tool, which is illustrated in several Egyptian tombs dating from the 5th to the 26th dynasty, and also shown as a determinative sign from the third dynasty onwards,[9] generally consisted of a straight wooden shaft that inclined at an angle near the top to form a handle. In its drilling configuration, a copper tube was force-fitted to the bottom of the shaft. The shaft and handle were created from a forked tree branch, adapted by cutting away the main stem just above the point where it branched into a lesser stem, which in turn was cut to length and carved into a distinctly tapered handle. The tool's main shaft was fitted with two stone weights, fastened under the handle. These weights placed a load upon a tubular drill and, consequently, upon the sand abrasive under the drill (Figure 3). After the hole's core had been removed, a forked shaft was lashed to the tool's main shaft. The fork generally engaged with figure-of-eight shaped stone borers (Figure 4), also in use with sand abrasive, although other borer shapes were employed.[10]

TABLE 2. Specimen drilling results

Stone	Ratio: copper: stone	Excavation rate: cm^3/hr
soft limestone	1:>100	30
hard limestone	1:>100	15
calcite	1:>100	30
rose granite	1: 3	2
diorite	1: 3	2

Experimental drilling of several hard and soft stones was carried out with copper tubular drills and sand abrasive.[11] The experiments determined that dry sand abrasive was more effective than wet sand abrasive; the tube and the manner of its use upon stone , particularly deep holes drilled into heavy objects, for example, sarcophagi, demonstrated that wet sand prevented the drilling

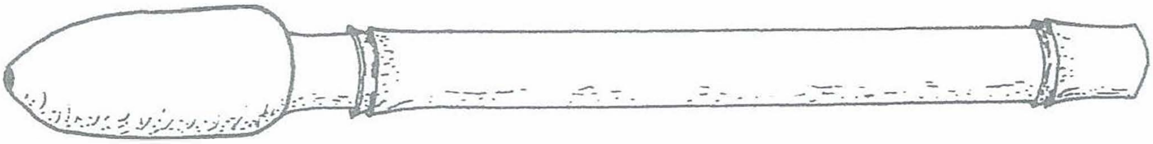


FIGURE 5. Experimental blowpipe with clay/mud nozzle.

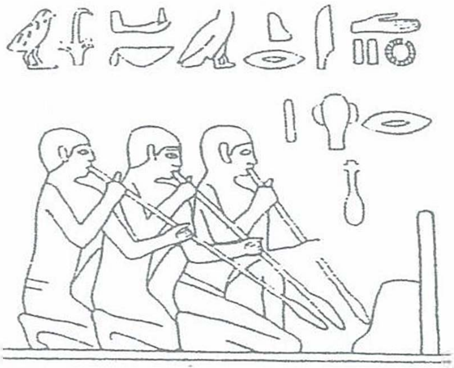


FIGURE 6. (Left). A jeweller and his blowpipe. (After Davies 1943: II, Pl. LIV, courtesy of the Metropolitan Museum of Art, New York).
FIGURE 7. (Right). 'Industrial' blowpipes for furnace work. (After Blackman and Apted 1953: Pl. XVI).

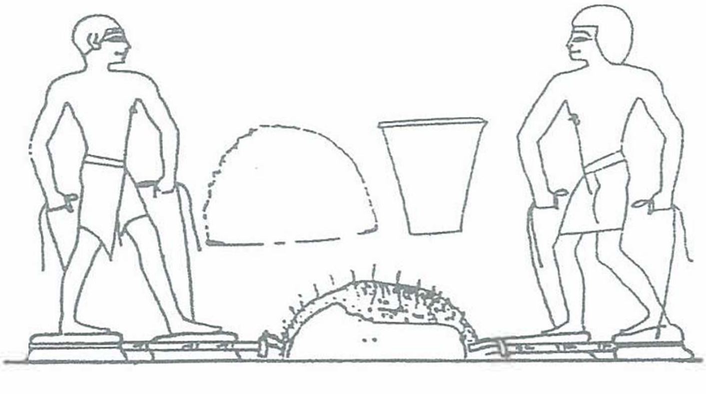


FIGURE 8. Men operating foot-bellows. (After Davies 1943: II, Pl. LIV, courtesy of the Metropolitan Museum of Art, New York).

process from working properly.[12] The volumes of copper worn off the drill-tube to stone excavated were used to obtain a ratio between the two materials.

Blowpipe experiments

The ancient Egyptian furnaceman developed two definite methods for blowing air into his furnace, which was not only in use for smelting ore, but also employed for melting copper for casting purposes. These two methods were the blowpipe and the foot-operated bellows of the 18th dynasty. In the predynastic period, the furnace in use may have been a bowl-shaped hole dug into the north facing side of a low hill.[13] Such a furnace hole could have been connected from the base of the furnace to the open air, at a point lower than the furnace-hole, by a funnel in order to admit wind which normally blows from the north most times of the year. However, there is no proof that this type of furnace ever existed. It is much more likely that predynastic furnaces were exclusively supplied with air from blowpipes.

Tomb illustrations dating from the Old Kingdom either show furnaces upon the ground's surface, or inside some form of fireplace, depicted in side elevation. These furnaces are all supplied by air from blowpipes. The 6th dynasty tomb of Mereruka at Saqqara depicts two crucibles placed back to back above the surface of the ground,[14] and it appears unlikely that such furnaces were associated by wind-driven air through funnels. In the 18th dynasty tomb of Hapu, two furnacemen are using blowpipes in conjunction with foot bellows;[15] this may indicate a large crucible full of bronze which required additional air to melt it.

Experiments were conducted with a reconstructed blowpipe manufactured from a bamboo cane (Figure 5), but in ancient Egypt blowpipes would have been constructed from the bamboo-like reed, Phragmites communis: tomb artists depicted blowpipes with clearly defined leaf joints.[16] Tomb representations also show that two types of blowpipe were in use. In the tomb of Rekhmire at Thebes, a jeweller's blowpipe measures approximately 60cm[17] (Figure 6), whereas an illustration in the 12th dynasty tomb of Pepionkh depicts 'industrial' blowpipes measuring approximately 1.5m in length[18] (Figure 7).

The experimental bamboo cane possessed an average external diameter of 2.5cm, an internal diameter of 2cm and a length of 56cm. The internal leaf joint partitions were broken through by the employment of a sharpened cane, measuring 1.5cm in diameter; it was longer than the blowpipe cane. I jabbed this tool through the partitions, effectively making the blowpipe cane a hollow tube along its whole length. The use of this simple solution for the removal of ancient reed leaf joint partitions cannot be directly proved, but any craftsman will solve technological problems in the most direct and simple way open to him. In fact, no other method can be employed to remove the partitions without damaging the tube.

I supplied the blowpipe with a clay/mud nozzle, which was fitted in ancient times to protect the organic material from intense heat; an 8mm diameter hole was made before the clay/mud dried hard. This diameter of nozzle hole cannot be proved either, but experiments demonstrated that it fulfilled the purpose admirably; it is likely that ancient hole diameters changed slightly from pipe to pipe. It is thought that pottery nozzles, which of necessity would have needed shaping and firing away from the flammable pipes before fitting to them, were not manufactured in ancient times.

What volume of air per minute would an ancient furnaceman deliver to his furnace by blowpipe? Experiments determined that a full breath (approximately 5 litres) could be discharged through the experimental pipe in one second. A sustainable rate of air delivery was found to be between 50-75l/minute. Any attempt to blow much more air than 75l/minute brought about the unpleasant effects of hyperventilation.[19]

The foot bellows

The foot bellows is an interesting development of furnace technology; good examples are shown in the 18th dynasty tomb of Rekhmire[20] (Figure 8). A large, shallow, flat-bottomed pottery bowl was fitted at the rim with a loose leather top. It was secured to the rim so as to be air tight. A long string was attached to the leather, at its centre. A small hole was cut into the leather, adjacent to the edge of the pottery bowl. Projecting from the bowl, towards the furnace, was a reed tube fitted with a clay/mud nozzle. A man operated two bellows, placed side by side, one with each foot. As the left foot squeezed air from its bellows the right foot was lifted upwards, together with the string held in the right hand. The hole in the leather admitted air into the bellows as the leather was raised. The right foot then squeezed air from the bellows through the nozzle by covering the hole with the heel ; the string was allowed to loosen as the foot descended. Meanwhile, the left foot and hand allowed the left bellows to expand in a similar manner to the right one. A natural rhythm ensured a good supply of air.

The admission of air into a melting furnace is crucial if its interior is to reach the temperature necessary to melt the metal contained in a crucible; copper requires a temperature of 1083°C. For bronzes containing varying amounts of tin, lower temperatures are sufficient. For example., a bronze containing 10% tin has a melting point some 80°C less than pure copper. Tylecote and Boydell,[21] who tested experimental furnaces based upon furnace shapes and sizes[22] discovered at Timna in the Negev desert, found that an air flow of 200l/minute, delivered through a tuyere, raised the furnace temperature to 1300°C, more than enough to smelt ore, or melt copper in a crucible. In my furnace, of similar dimensions to the Timna furnaces, it was found that an air flow of 200l/minute enabled the furnace to melt lkg of copper. This furnace also possessed a maximum melting capacity of 2kg of bronze, if operated with an air flow of 600l/minute.

The main limitation to a furnace's ability to melt copper is the volume of air that constantly can be maintained during the melting process. Tomb illustrations, dating from the 5th to the 18th dynasties,[23] depict furnacemen blowing air by blowpipes into furnaces. Without the benefit of wind assistance, and before foot bellows were employed in the 18th dynasty, melting capacity must have been directly connected to the number of furnacemen employed for blowpipe duty. In the 6th dynasty tomb of Mereruka, six men have been supplied with blowpipes. This number of men could provide, if each man blew air at the experimentally determined rate of 50-75l/minute, a total of 300-450l/minute, enough to melt more than 1kg of copper in one crucible. The 12th dynasty tomb of Pepionkh depicts three men blowing through pipes and the 18th dynasty tomb of Hapu shows two men supplying air, but in conjunction with a bellows. The tomb of Rekhmire depicts a single jeweller using a blowpipe at his small brazier set upon a low support. However, this man is not melting metal, but engaged with heating it before soldering.

The tests indicate that three or more ancient furnacemen could supply enough air to melt useful amounts of copper without any other assistance, and tomb artists portrayed numbers of men blowing air into furnaces that must have been an accurate reflection of observed situations.

Some other ancient uses of copper tubes

In the 4th dynasty tomb of Khufu's mother, Hetepheres, the cylindrical sockets in which the upright poles of her canopy rested were made from sheet copper. Each longitudinal, overlapping joint was silver soldered. [24] The tube of a copper trumpet, found in the 18th dynasty tomb of Tutankhamun, was also soldered together in a similar fashion. A length of copper pipe 102cm long, 4.7cm in diameter, with a wall thickness of 1.4mm, was found in the 5th dynasty complex of Sahure; this pipe was part of a water conduit, designed to carry excess rain-water away from the pyramid.

Conclusions

The introduction of long, hollow cylinders, or tubes, has greatly influenced Man's technical ability. By breaking through the leaf joint partitions in a reed stem, thereby joining together the existing hollow sections to create a continuous tube, the ancient craftsman manufactured a radically new artefact. Today, tubes are made from a variety of materials, which include copper, brass, aluminium, mild and stainless steel and plastic. Tubes, or pipes, are in use for many purposes, from conducting water, gas, oil and other industrial substances to scaffolding and hang gliders.

Comparisons between the drilling results for reed tubes and copper ones demonstrate how superior the copper copy is to the reed, which is unable to penetrate hard stone. The ability of the craftsman to drive copper tubular drills and stone borers with the TRTD, which replaced older methods of driving tubes and borers,[25] meant that hard and soft stone vessel production expanded rapidly during the Naqada II period. Reed tubular drills only operate effectively using dry sand as an abrasive. Wet sand quickly destroys the structure of the tube. It would be natural for the craftsman to continue with dry abrasive for drilling with copper tubes, and dry sand was found to possess superior drilling qualities in association with these tubular drills (see note 12).

The reed as a blowpipe, and the copy of the reed drill-tube in copper, fundamentally changed the direction of ancient Egyptian technology, and the development of Egyptian civilisation. Without the blowpipe in the predynastic period, it is unlikely that furnaces could have been made hot enough for the length of time required to melt useful amounts of copper for casting, and without the ability to cast copper sheets large enough to work into tubes, or directly cast them, the craftsman could not have expanded stone vessel production in hard stone. A primitive furnace, solely dependent upon wind for its air, is unlikely to have maintained the necessary heat to melt substantial amounts of copper contained in a crucible.

The tubular drilling of hard and softer stone, by the TRTD, considerably reduced the time and effort to excavate vessels' interiors. Huge numbers of vessels were produced, particularly in the first two dynasties. Additionally, the driving of large diameter copper tubes,[26] by a bow, allowed craftsmen to excavate hard stone sarcophagi, beginning in the third dynasty with Sekhemkhet's calcite sarcophagus and graduating, a dynasty later, to Khufu's rose granite sarcophagus, which is still inside the Great Pyramid of Giza.

References

1. Stocks 1988, 63; Lucas 1962, 74; Reisner 1931, 180. The evidence for copper tubular drills is incontrovertible. It is highly improbable that a tube of copper was suddenly invented without a prototype shape to copy. The copper tube must be viewed as a copy of a tube which was already in use for drilling stone.
2. Tackholm 1973, 210
3. Sand was the only naturally occurring particulate abrasive substance easily available in unlimited quantities to ancient craftsmen. Its abrasive qualities were already well known. The craftsman was aware that wind-blown sand abraded rock, and that quartz sand particles in bread ground away his teeth.
4. Stocks 1988, 139.
5. Stocks 1988, 137-40. The reed results which closely match the bamboo results, postdate the experimental data contained in my thesis. The bamboo results are published here directly from the thesis.
6. Stocks 1986a, 7 (4) 16.
7. Hoffman 1980, 303.
8. Stocks 1986, 7 (3), 27; 1986a, 7 (4), 17.
9. For example, a third dynasty hieroglyph in Firth et al. 1935, I, Pl. 93. A representation from a fifth dynasty tomb at Saqqara (Cairo Museum JE39866); Steindorff 1913, Pl. 134; Duell 1938, I, Pl. 30; Davies 1902, I, Pl. XIII; Blackman 1914, Pl. V; Blackman and Apted 1953, Pl.XVI; Davies 1943, II, Pl. LIV; Davies 1925, Pl. XI; Davies 1922, I, Pl. XXIII; Davies 1902, I. Pl. XXIV.
10. For example, a conical-shaped borer.
11. That sand was the abrasive in use with copper drills has been confirmed by the finding of copper compounds in sand powders associated with drilling activity.
12. Dry sand abrasive allows the smooth interchange of worn quartz crystals with new ones; wet sand drying out prevents this phenomenon from occurring. Very wet sand will interchange at the cutting face, but cannot be withdrawn from deep holes in sarcophagi. Dry, finely ground sand powder sticks together inside a tube and can be withdrawn. Fluid sand powder remains in the bottom of a hole and clogs it up.
13. Mond and Myers 1937, I, 167.
14. Duell 1938, I, Pl. 30.
15. Coghlan 1951, Fig. 10.
16. Davies 1943, II, Pl. LIII.
17. Davies 1943, II, Pl. LIII.
18. Blackman and Apted 1953, Pl. XVI.

19. Hyperventilation occurs when too much carbon dioxide is removed from the body by excessive breathing. Carbon dioxide is essential for the central nervous system to operate correctly. The condition causes dizziness and paralysis.
20. Davies 1943, II, LII.
21. Tylecote and Boydell 1978, 27-51.
22. Furnace A had an internal diameter of 32cm and furnace B had an internal diameter of 22cm.
23. Davies 1943, II, Pl. LIII (one pipe); Coghlan 1951, Fig, 10 (two pipes); Blackman and Apted 1953, Pl. XVI (three pipes); Davies 1902, II, Pl. XIX (four pipes); Duell 1938, I, Pl. 30 (six pipes).
24. Lucas and Harris 1962, 215-6.
25. Tubes and borers were twisted by gripping each tool type directly in the hand.
26. Petrie 1883, 84; 1884, 93; Stocks 1988, 148-51, Figs. 23-5. The drill-tube used to excavate Khufu's sarcophagus measured 11cm (1.5 ancient royal palms) in diameter.

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Notes

Derivation of ancient Egyptian faience core and glaze materials

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An essential ingredient of the lovely blues in ancient Egyptian materials — faience, glazes, frits — is copper. How did the knowledge of that copper use arise? There is a telling congruence with Egyptian techniques in drilling stone artefacts, and the characteristics of the powder drilled out as waste.

An enigma of ancient Egyptian craftsmanship is the origin of the materials used for faience cores (bodies) and glazes. Ancient Egyptian dynastic craftsmen used copper tubular drills, with sand abrasive, to excavate stone artefacts (Petrie 1917: 45–6; Lucas 1962: 74; Reisner 1931: 180); the waste powders, rich in quartz, also contained copper from the drills. Did ancient craftsmen use these for other purposes? This article proposes that the powders make faience cores and blue glazes and, perhaps, blue frits. To explore this possibility, the characteristics of ancient faience are compared with the microstructure and composition of experimentally made ceramics.

Ancient faience: a brief description

Faience was employed to make jewellery, statuettes, small vessels and tiles, which were mostly blue or green. The first ancient Egyptian glazed material, found by Brunton & Caton-Thompson (1928: 27–8, 41) in grave deposits dated to the Badarian culture of Upper Egypt (*c.* 5500–4000 BC), consisted of carved and drilled steatite beads covered by a transparent and glossy glaze. It appears clear in cross-section, but in looking directly at the surface the optical effect is of translucency (Vandiver & Kingery 1986: 20, figures 1, 3). Glazes containing malachite (a copper ore) produced the greenish-blue colour which imitated the rarer lapis lazuli and turquoise (Vandiver & Kingery 1986: 20).

About 4000 BC, stone cores were replaced by ceramic ones, made mainly from finely divided (ground) sand, but occasionally of comparatively coarser sand, which was modelled into shapes; cores also contain minor amounts of lime and either natron — a naturally occurring alkaline mixture of sodium salts, carbonate, bicarbonate, chloride and sulphate — or plant ashes. Often very friable, they are frequently white, or practically white in colour, but can be tinted brown, grey, yellow, sometimes very slightly blue or green (Lucas 1962: 157; Kaczmarczyk & Hedges 1983: 123; Vandiver & Kingery 1986: 20). In the core, minute angular particles of quartz are bonded together by varying amounts of interstitial glass, and covered with an alkali-based glaze, typically coloured blue by copper (Tite 1986: 39; 1987: 23–4).

A summary by Vandiver (1982: 167) of a composite range of chemical analyses of the body shows 92–99% SiO_2 (silicon dioxide), 1–5% CaO (calcium oxide), 0·5–3% Na_2O (sodium oxide), with small quantities of CuO (copper oxide), Al_2O_3 (aluminium oxide), TiO_2 (titanium dioxide), MgO (magnesium oxide) and K_2O (potassium oxide). Most authorities accept faience firing temperatures of 800–1000°C (Vandiver 1983: A10–11, A26ff). A significant number of ancient Egyptian faience cores (Tite & Bimson 1986: 69) show that many particle sizes are less than 50 μm diameter; even when coarser-grained quartz (100–200 μm diameter) predominates, significant amounts of fine-grained quartz, less than 50 μm diameter, are still present (Tite & Bimson 1986: 69). Dynas-

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tic cores, moulded, or modelled, from a stiff paste (Petrie 1909: 115–16, 118–19), were glazed by efflorescence (the firing of a core containing a glazing component, which partially rises to the surface during drying and fuses to become the glaze), or by cementation (the firing of a dry core buried in a glazing powder), or by direct application of a glazing slurry to a dry core's surface before firing.

The glaze consists of a soda-lime-silica mixture (Vandiver 1982: 167), generally 60–70% silica, 16–20% soda and 3–5% lime (Tite pers. comm.). Copper oxide content is variable. Lucas's (1962: 475) analysis of a Nineteenth Dynasty tile's glaze showed 1·1% CuO; analyses by Vandiver & Kingery (1986: 29, table II) of faience glazes ranging from the predynastic to the New Kingdom period found the lowest CuO content 1·5% (average of 5 pieces) and the highest 18·1% (average of 4 pieces).

Experiments with copper tubular drills and sand abrasive

Previous experiments with copper tubular drills, driven by a bow and a stone vessel drilling tool (Stocks 1986a: 24–9; 1986b: 14–18), indicate that sand was utilized in the *dry* state (Stocks 1986a: 27; 1988: 124–9); it is probable that dynastic craftsmen used sand in a comparable manner. The product of drilling is a fine, cohesive, flour-like powder, mostly quartz, but with small amounts of copper, that packs inside the tube and can easily be removed from the hole (Stocks 1993a: 600).

It is likely that the hollow common reed (*Phragmites communis*) was in use with dry sand (wet sand softens and destroys the woody stem) for drilling calcite and hard limestone in the predynastic period, before copper tubes were invented; a reed tube performs well upon these stones (Stocks 1993b: 59–60, table 1). The rapid increase in the production of *hard* stone vessels in the Early and Late Gerzean periods (*c.* 3500–3050 BC) indicates that the reed's tubular design was copied in copper; reed tubes are not practical for drilling hard stone, but copper tubes excavate it at an acceptable rate (Stocks 1988: 133–6, 340). Lucas confirmed the use of copper tubes on hard stone when he found green patches on a red granite core at Saqqara (1962: 69). Although there is no trace of any predynastic copper *drill-tubes*, a Gerzean copper tubular bead, now in the Petrie Collection (University College London, UC 5066), was excavated from a grave at Naqada; it proves that the techniques for making copper tubes were understood and practised by Gerzean craftsmen. Later in dynastic history, the craftsman employed bronze tubes (Arnold 1991: 266, figure 6.20).

A small granite block was drilled with sand, which contained quartz crystals mainly 0·13–1·27 mm in diameter; the hard limestone and calcite samples were drilled by a different sand, which contained crystals mainly 0·16–0·69 mm in diameter. In hard stones, e.g. granite and basalt (both hardness Mohs 7), the ratio of the *weight* of copper worn from a drill-tube to the *weight* of stone drilled is 1:0·9. Hard stone derived powders, dark grey (granite) or nearly black (basalt) in colour, have the appearance and feel of powdered emery; hard limestone — and calcite — derived powders are almost white, tinged slightly brown by the colour of the sand. In hard limestone (hardness Mohs 5) and calcite (hardness Mohs 4), the weights of copper worn away to the weights of drilled stone are 1:8 and 1:12 respectively. It is clear, from tests and subsequent calculations, that the employment of drill-tubes over millennia constantly depleted copper resources.

In drilling tests the powdered product contained, on average, by weight, for granite, 97·70% sand, 1·10% stone, 1·20% copper; hard limestone 94·46%, 4·93% and 0·61%; for calcite 94·10%, 5·43% and 0·46%. The usual amounts of sand consumed to excavate 1 cu. cm of granite, hard limestone and calcite were 200–250, 50 and 45 g respectively, and the times for excavating 1 cu. cm 40, 5 and 2 minutes respectively.

If any quantity of sand is ground until a roughly homogeneous powder is produced, then most particles are 50–150 μm in diameter with some of approximately 200 μm; a further short grinding period rapidly reduces most particle sizes to 50–80 μm. An experienced craftsman could distinguish, by listening to the sounds of grinding, and noticing the feel of the drilling action, whether the powder is ground to these fine dimensions: at this point the powder, exhausted as an effective abrasive for tubular drilling, can be used for polishing stone and drilling beads (Stocks 1986b: 17; 1989: 528, 530).

Experimental faience manufacture

After some unsuccessful experiments, it was found that a stiff paste, made from a mixture of 99% of the powder obtained from drilling hard limestone, or from calcite derived powder, and 1% $NaHCO_3$ (sodium bicarbonate), produced a practically white, friable core. Af-

	calculated composition			**mean bulk analyses**	
	core	**glaze**		**core**	**glaze**
SiO_2	93·56%	73·80%	SiO_2	90·25	74·55
Al_2O_3	–	0·11%	TiO_2	0·01	0·05
Na_2O	0·37%	9·23%	Al_2O_3	3·47	0·08
Cu	0·59%	0·90%	FeO	0·00	0·42
CaO	2·72%	–	MnO	0·00	0·35
			MgO	0·20	0·00
			CaO	4·35	12·04
			Na_2O	0·95	11·10
			K_2O	0·52	0·86
			P_2O_5	–	0·00
			SO_3	–	0·01
			CuO	0·24	0·54

TABLE 1. *Calculated composition and bulk composition analyses of the experimental faience core and glaze. They were made from powders derived from the drilling of hard limestone and granite with a copper tube and sand abrasive. The hard limestone powder contained 94·50% SiO_2 (quartz), 4·90% $CaCO_3$ (limestone) and 0·60% Cu (copper). The granite powder contained 97·70% SiO_2 (quartz), 1·10% granite and 1·20% Cu. (Analysis of the glaze by Chris Doherty; analyses of the core and the glaze by courtesy of M.S. Tite and the Research Laboratory for Archaeology and the History of Art, Oxford University).*

ter drying, each core was fired to a temperature of 850°C, and allowed to cool without soaking. Analysis of the core made from the hard limestone derived powder (TABLE 1) found it similar to ancient faience in microstructure, especially in quartz angularity and particle size (FIGURE 1). The bulk composition is similar, with slightly lower silica and higher lime (Tite pers. comm.).

An experimental glaze, made with 75% granite derived powder and 25% $NaHCO_3$ (TABLE 1), was made runny and directly applied to an unfired core. This glaze was made from a drilling powder containing copper produced several years before and including some quartz particles up to 200 µm diameter. When the sample was fired at 950°C, without a soak time, a deep blue vitreous glaze was created (FIGURE 2). Further grinding would soon have reduced the quartz and copper to smaller particles, improving the glaze's appearance by a more uniform dispersal and dissolution of the copper.

Conclusions

The experimental faience manufacture indicates that the powders derived from drilling hard limestone and calcite are ideal for making cores, and that hard stone derived powders (more copper particles) are suitable for blue glazes. The powders are satisfactorily ground to the particle sizes and angularity seen in ancient faience cores, and the composition of the experimental core is similar to ancient faience.

FIGURE 1. *SEM photo of the core, made from hard limestone derived powder. Scale bar = 50 µm. (Photo courtesy of M.S. Tite and the Research Laboratory for Archaeology and the History of Art, Oxford University).*

Since both faience and *Egyptian blue* frit are made essentially from the same raw materials (Tite 1987: 30), it could be that the frits were manufactured from waste drilling powders that contained more lime, i.e., from the sand and drilled stone. An increased copper content

FIGURE 2. *The glaze sample, made from granite derived powder.*

would give a suitable frit powder; differences in the details of the frit's microstructure, mineralogy, texture, hardness and colour would depend on the relative amounts of SiO_2, CaO, CuO and alkali, on the particle size of the powder and on the temperature and length of firing (Tite 1987: 27).

After *c.* 3500 BC, craftsmen did not have to produce special powders for faience, or frit, because the powders required were available as a by-product from the drilling of stone by copper tubes. The ability to model quartz-based powders into cores probably initiated a change from carved steatite ones; blue and green glazes, made from copper-contaminated drilling powders, possibly supplanted earlier methods of colouring them. The expansion of stone vessel making in the Gerzean period may have caused a commensurate increase in faience production; although there was a decline in hard stone vessel manufacture during the Early Dynastic period, the making of calcite vessels continued unabated. The construction of hard stone sarcophagi from the Fourth Dynasty onwards, and other artefacts made by drilling and sawing with sand abrasive, continued to make the powder available.

If indeed the waste powders from drilling were the basis for ancient faience, then the varying mineralogical content seen in these ceramics can be traced to differences in the drilled stones and the sand abrasive. Also, the metallurgical content of the coppers and bronzes used to make tubular drills, whether from newly smelted ores, or scrap metal obtained from worn tools, would be different for each tube.

Although the ancient use of these powders cannot *directly* be proved, the experiments indicate that they should be considered as a material employed for some ancient faience.

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BARBARA S. LESKO

stone vessels and bead making

In every period the shaping of all hard stone vessels, including those manufactured from basalt, diorite, porphyry, breccia, granite and Egyptian alabaster (calcite), was completed by flint chisels, punches and scrapers. Flint was the only abundantly available tool-making material which was satisfactory for the exterior shaping of hard stone vessels. After 3,600 BC, Egyptian craftsmen learned to cast copper tools, but tests with hardened and sharpened copper chisels have demonstrated their inability to effectively cut any stone used for vessels, other than soft limestone and gypsum. Even these stone vessels needed awkward places to be shaped by flint scrapers; necks, rims and the undercutting of vessels' shoulders all required skilled carving techniques. After preliminary shaping, coarse and smooth sandstone rubbers were utilized to complete this process and initiate surface polishing, which was probably finished by a sand/stone/copper powder used wet, followed by clay/mud, both applied by leather laps.

The technology for hollowing vessels was fully established in the Predynastic period. During the early Predynastic phases (Badarian and Nagada I) hard stone vessels would have been laboriously hollowed by hand-held stone borers, used in conjunction with desert sand abrasive; hand-held flint borers would have been used for very soft stone, without the benefit of sand abrasive. However, before the advent of copper tubes by the mid-fourth millennium BC (Nagada II), craftsmen possibly employed a reed tube, also in use with sand abrasive. This tube could have been spun between the hands, twisted by wrist action or driven by a bow. Reed drills will efficiently cut limestone and calcite, but not the harder stones, such as granite and porphyry.

After the introduction of cast copper, the stone vessel craftsman was able to imitate the hollow reed by beating thick sheets of cast copper into thin sheets and rolling them around wooden, cylindrical formers. Larger diameter copper tubes may have been directly cast by making tubular-shaped molds in damp sand. A wooden shaft was then forcibly driven, partway, into the tubular drill. This allowed the drill to be rotated by a bow, the upper part of the shaft turning in a hand-held, stone bearing-cap.

The tubular drill produces a tubular-shaped slot, which surrounds a central core. This technology allows the removal of a small amount of stone by drilling, but achieves the full-sized hole on removal of the core. The bow-driven copper tubular drill was certainly used to drill the holes in tubular lugs carved into vessels in Nagada II times. However, holes and cores produced by bow-driven tubes are tapered, caused by a motion actuated by the push and pull of the bow, and, as vessels were always shaped before drilling of the interior commenced, there was a severe risk of damaging them. Additionally, experiments have demonstrated that bow drilling also causes quartz sand crystals, trapped between the outer wall of the tube and the wall of the hole, to elongate the originally circular hole, thereby meeting the external wall of a shaped vessel.

Clearly the stone vessel craftsman needed a special tool to drive his tubular drills and stone borers which did not suffer from these drawbacks. During Nagada II times, a combined vessel-drilling and boring tool was developed by craftsmen. The tool, which is illustrated in several Egyptian tombs dating from the 5th to 26th Dynasties, generally consisted of a straight wooden shaft that inclined at an angle near the top to form a handle. The shaft and handle were created from a forked tree branch, adapted by cutting away the main stem just above the point where it branched into a lesser stem, which in turn was cut to length and carved into a distinctly tapered handle. The tool's main shaft was fitted with two stone weights, fastened under the handle. These weights placed a load upon a tubular drill or stone borer and, consequently, upon the sand abrasive under the drill and borer. A single, circular weight was introduced during the 12th Dynasty.

Although tubular drills were fitted directly to the tool's main shaft, borers were driven by a forked shaft lashed to the bottom of the main shaft. The principal borer for enlarging the initial cylindrical hole was shaped like a figure-of-eight when viewed from the top. The fork engaged on each side of the borer, which was deliberately fashioned from an oval pebble. Other types of borers were circular and conical, the latter shape being in use to enlarge vessels' mouths. Cylindrical vessels of soft stone, such as gypsum, would have been completely excavated by crescent-shaped flint borers. Worn forked shafts could be replaced when necessary, and this stratagem ensured the continued use of the main tool.

In order to operate the tool, one hand firmly gripped the handle while the other hand gripped the shaft under the weights. The tool's shaft was then twisted and reverse-twisted by a continuous wrist action. Extensive tests have established that wet sand abrasive is not conducive to the efficient drilling and boring of stone, and it is highly likely that dry sand was used. Different diameter drill tubes, on the same axis, were probably used to weaken a large core, and a vessel with a large mouth had a series of adjacent holes drilled around the perimeter to isolate the central mass. After drilling, figure-of-eight shaped borers of ever-increasing lengths were utilized to bore out bulbous vessels. Hand-held, hook-shaped flint and other stone borers were employed to complete the undercutting of vessel shoulders.

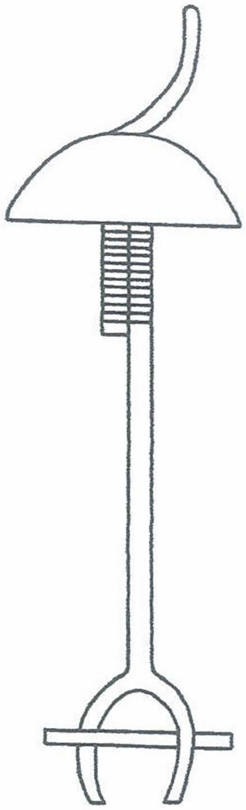

Figure 108 An 18th Dynasty representation of the stone vessel drilling and boring tool

Experiments have determined that tubes and borers ground the sand abrasive and stone into a finely powdered material, which must have caused lung damage to ancient craftsmen. Powder produced by copper tubes also contained fine particles of copper. Significantly, the by-product powder produced from drilling granite contains approximately twelve times the amount of copper in powder obtained from drilling soft limestone, and this enabled other ancient craftsmen to use different powders for stone polishing, bead drilling and, possibly, faïence manufacture.

Bead making began in Epi-paleolithic times (*circa* 10,000–5,500 BC). At first craftsmen utilized natural objects, such as pebbles, shells and teeth. In the Predynastic period, beads were also made from copper, gold, silver, greenish-blue glazed quartz and stones (agate, calcite, carnelian, diorite, garnet, limestone and serpentine). The Egyptians' most favored bead shapes were rings, barrels, cylinders, convex bicones and spheroids, but amulets and pendants were also threaded into strings. Glass beads were introduced during the Dynastic period, and they were made by winding a thin thread of drawn-out glass around a wire.

Experiments have demonstrated that the powdered by-product material, when mixed with sodium bicarbonate (natron in ancient times) and water, creates faïence cores and glazes after firing. Ancient faïence bead, amulet and pendant cores could have been manufactured from powders derived from drilling soft stone with copper tubes. In ancient times a stiff paste, with a thread, wire or awl initially inserted to make the perforation, was molded or modeled into shape, and then glazed with a runny paste probably manufactured from powders derived from drilling hard stone. After firing, cores turned into a hard, whitish material that was sometimes tinted blue, green, yellow, brown or gray, while glazes turned mainly blue or green due to an increase in copper content.

Metals can be shaped by hammering, but hard stone beads were first formed by breaking up pebbles, then roughly shaping the pieces by chipping with flint tools, followed by grinding on harsh and smoother grades of sandstone. Final polishing was achieved by rubbing along grooves in wooden benches coated with a runny polishing abrasive, possibly made by mixing by-product powder with muddy water.

Perforation of stone beads was accomplished by flint borers from the earliest periods, but the use of bow-driven copper drills first appeared in early Predynastic (Badarian) times. Even so, flint borers were concurrently in use with copper drills and were also needed to make initial depressions in beads to center these drills. A thin abrasive paste, probably made from the by-product powder, was used with copper and bronze bead drills. At Kerma, in Nubia near the Third Cataract, small bronze drills were force-fitted into waisted wooden handles which were individually driven by a bow string, but by the 18th Dynasty at Thebes, craftsmen evolved mass-production drilling technology. The bow's length was increased to approximately 1.2 m; its 2 mm diameter string simultaneously turned two, three, four, or even five bronze drill rods, each 5 mm in diameter. These rotated in bearing holes drilled into the bottom ends of vertical sticks, held in line by the craftsman's free hand. The drills revolved at high speed in stone beads secured in the top of a three-legged table. Mass production of bead perforation considerably reduced the time, and cost, of bead making.

See also

Dynastic stone tools; faïence technology and production; jewelry; metallurgy; Neolithic and Predynastic stone tools

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Stone sarcophagus manufacture in ancient Egypt

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Experimental work on the techniques for making stone sarcophagi demonstrate how a variety of tools, material and drilling methods were employed in ancient Egypt.

Key-words: Egypt, stone, sarcophagi, drill, saw, metal, tools

The creation of sarcophagi from single blocks of stone, particularly the hard, igneous varieties, was accomplished by the development of stone sawing and drilling skills: the saws and drills for working hard stone, and indeed illustrations of the processes, have never been discovered by archaeologists. An examination of ancient sarcophagi, particularly the tool marks left on them, helped reconstruct copper saws and tubular drills for test on different types of stone. Stone sarcophagi were also carved with hieroglyphs and reliefs, both internally and externally. These techniques were investigated by comparing the relative capabilities of replica copper, bronze and iron chisels to reconstructed flint chisels, punches and scrapers for cutting different stones.

Monolithic stone sarcophagi were first introduced in the Third Dynasty (*c.* 2686–2613 BC), being constructed from soft white limestone (hardness Mohs 2·5) and calcite (Egyptian alabaster, Mohs 4). In the Fourth Dynasty (*c.* 2613–2494 BC), Cheops' (*c.* 2589–2566 BC) craftworkers manufactured the first sarcophagus of granite (Mohs 7), an igneous stone. Subsequent sarcophagi were made from these three stones, along with basalt, quartzite (both Mohs 7) and greywacke (Mohs 4–5). Soft limestone, calcite and granite represent ascending degrees of difficulty in making sarcophagi; consequently, these stones were experimentally sawn, drilled and cut in investigating ancient shaping, hollowing and relief carving techniques by ancient stoneworkers.

Shaping stone sarcophagi and surface decoration tools and techniques

Assessments of the performance of ancient copper and bronze chisels, traditionally thought to cut hieroglyphs and reliefs into stone, were made by experimenting with replica copper, leaded bronze and bronze chisels (Stocks 1986c: 25–6). They demonstrated that all stones of hardness Mohs 3, and below, could speedily be cut, including soft limestone. However, stones of Mohs 4, and above, cannot efficiently be cut by such metal tools; test tools' cutting edges were blunted, or torn away, to such an extent that constant sharpening, even for cutting calcite, caused unacceptable losses of metal from the tools. Other experiments (Stocks 1986c: 26) revealed that iron, or even steel, chisels were useless against igneous stone, such as basalt and granite, suffering considerable damage to their cutting edges.

Tests with dolerite and diorite tools by R. Engelbach (1923: 40) and A. Zuber (1956: 195) indicated a poor ability to cut granite. Zuber (1956: 180, figures 18–20) cut granite with flint (Mohs 7) implements, and my own experiments with flint chisels, punches and scrapers on granite, diorite, hard and soft limestone, hard and soft sandstone and calcite (Stocks 1986c: 25–9; 1988: II, 246–73, plates XXIV, b, XXV, b) revealed that flint tools can satisfactorily work all these stones, but that the cutting of igneous stone is a slow process. These findings support the shaping and hollowing of soft limestone sarcophagi by copper adzes and chisels, but it is possible that these sarcophagi were also worked by flint chisels, adzes and scrapers (Petrie 1938: 30). Flint chisels, punches and scrapers were necessarily used to carve hieroglyphs and reliefs on the internal and external surfaces of hard stone sarcophagi (e.g. the recessed palace-façade panelling on the Fourth Dynasty rose granite sarcophagus of Prince Akhet-Hotep, Brooklyn Museum 48.110; incised hieroglyphs inside greywacke and granite sarcophagi, Musée du Louvre N345 D9, N346 D10).

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and also to shape anthropoid sarcophagi from the Middle Kingdom onwards.

There are chevron-shaped sawing marks on Sekhemkhet's calcite sarcophagus (Goneim 1956: 108), and linear striations, or grooves, on the sides and ends of Cheops' granite sarcophagus, and other hard stone objects located at Giza (Petrie 1883: 174–5, plate XIV, 1, 2). These striations, and other evidence for copper saws and tubular drills in use with sand abrasive (Petrie: 1883: 174–5; Reisner 1931: 180; Lucas 1962: 74), indicate that a flat-edged copper saw cut Sekhemkhet's and Cheops' sarcophagi to shape. Ancient striations are about 0·25mm wide and deep, and have been duplicated in granite by reconstructed flat-edged copper and bronze saws and flat-ended tubular drills, both tools utilizing dry sand abrasive (Stocks 1986a: 24–9; 1988: I, 100–143). W.M.F. Petrie (1883: 84) suggested that the saw must have been '. . . about 9 feet long' (2·7m), allowing for it to be moved to and fro. Petrie (1883: 174–5) also stated that, from his observations of the dimensions of saw slots and tubular drill holes in stone, maximum saw and tube wall thicknesses were both '1/5 inch' (5 mm). For a long saw, a thickness of 5 mm is necessary for rigidity; interestingly, flat-edged saw blades are automatically cast to this thickness when molten copper just covers the bottom of a shallow, open mould (Stocks 1988: I, 57, II, plate II, a). Experiments with serrated copper saws show that they only effectively cut soft limestone, red sandstone, steatite and all soft and hard woods (Stocks 1988: I, 96, II, 295–8, 360–61): serrated copper or bronze saws soon suffer damage on calcite, or any stone of hardness Mohs 4, and above.

Some lids were sawn from the bottoms of previously shaped stone sarcophagi (e.g. a partially sawn broken lid, still attached to the bottom of a hollowed Fourth Dynasty rose granite sarcophagus, Cairo Museum JE54938), and lifting holes were sometimes drilled in each raised end by a bow-driven tube (e.g. a Third Dynasty calcite sarcophagus lid, Cairo Museum JE28102). Other lids generally were left with their lifting bosses still attached (e.g. a Fourth Dynasty rose granite sarcophagus, Cairo Museum JE48078).

Hollowing hard stone sarcophagi interiors

The use of stone mauls for pounding calcite, granite, basalt, quartzite and greywacke from the interiors of sarcophagi is impracticable: the force of the blows would soon have cracked the shaped stone blocks. The use of flint chisels and punches would have taken far too long to excavate such a large mass of stone. Therefore, Egyptian craftworkers employed the copper tubular drill for hollowing Sekhemkhet's calcite sarcophagus, a tool that had served them well since Gerzean (*c.* 3600–3050 BC) times for hollowing hard stone vases, and drilling holes in vessels' lug handles (e.g. syenite vessel, Manchester Museum 1776). The marks of tubular drills can be seen in Sekhemkhet's and Cheops' sarcophagi (Goneim 1956: 124; Petrie 1883: 84).

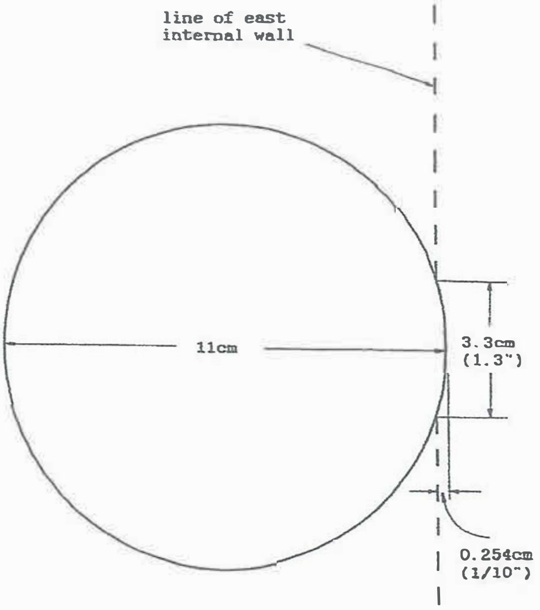

FIGURE 1. *The calculated external diameter of the copper tube in use for drilling Cheops' sarcophagus, with W.M.F. Petrie's measurements of the curved mark in the internal wall.*

Petrie (1883: 86) recorded the internal and external measurements of Cheops' sarcophagus. The metric equivalents of the internal length, width and depth were 198·3, 68·1 and 87·4 cm respectively, and the external length, width and height were 227·6, 97·8 and 105·0 cm respectively. The weight of the shaped block, before hollowing, was 6310 kg, where granite's specific gravity is 2·7g/cu. cm. The excavated stone weighed 3186 kg, leaving a finished weight of 3124 kg.

A curved mark in the eastern inside wall of Cheops' sarcophagus was measured by Petrie

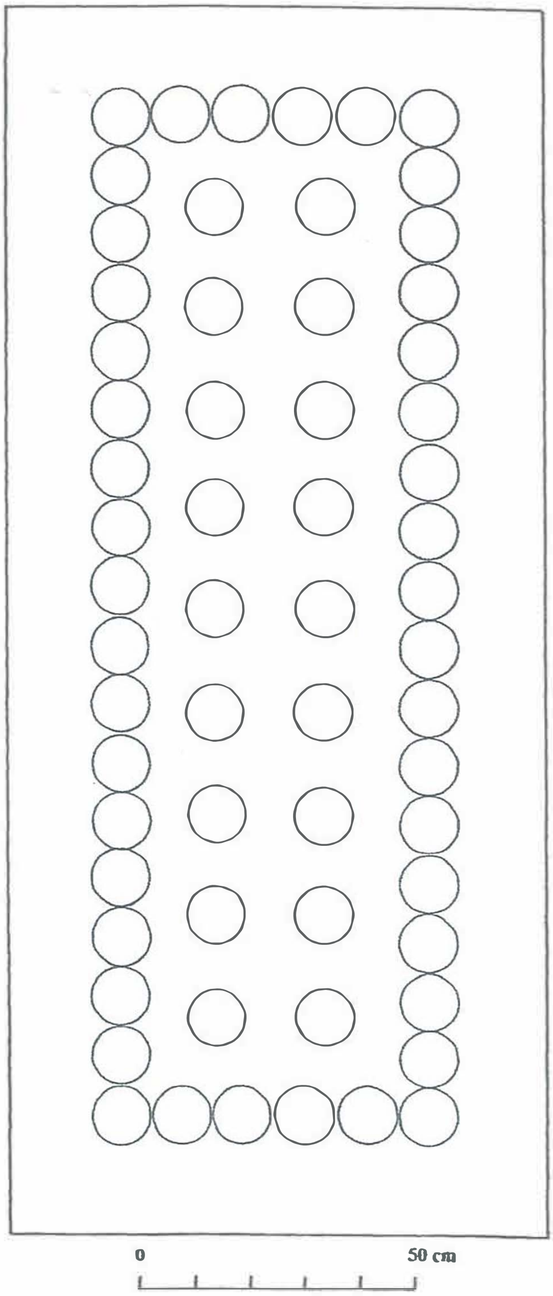

FIGURE 2. *The proposed method of drilling Cheops' sarcophagus by 62 holes, 44 for the perimeter, 18 to weaken the central mass.*

(1883: 84), in inches, to be '1/10 (2·54mm) deep, 3 (7·6 cm) long, and 1·3 (3·3 cm) wide', the bottom of it at a depth of '8·4 inches (21·3 cm) below the top of the block' (Petrie 1884: 93). Trigonometrical calculations, using Petrie's measurements (FIGURE 1), indicate that a tubular drill measuring 11 cm, very close to a measurement of six royal fingers, or one and a half royal palms, in diameter was employed for drilling the granite (Stocks 1988: I, 148–50, figures 23, 24). The metric measurement of a royal finger's width is 1·87cm, calculated by dividing the number of fingers, 28 in a royal cubit, into its metric length of 52·3cm (James 1979: 123). The wall thickness in this diameter tube was probably 5 mm: tubes of this diameter and wall thickness can be cast into vertical tubular moulds in sand (Stocks 1986a: 26–7). An 11-cm diameter tube fits almost exactly 18 and six times into the internal length of 198·3 cm (26·5 royal palms) and the width of 68·1cm (9 royal palms) respectively (FIGURE 2). This finding is supported by dividing the same diameter tube into the internal length and width of the Twelfth Dynasty (*c*. 1985–1795 BC) rose granite sarcophagus of Sesostris II (*c*. 1897–1878 BC) at Lahun. This tube diameter fits precisely 19 and six times into the internal length of 209·5 cm (28 royal palms) and the width of 67·4 cm (9 royal palms) respectively. It is possible that a six royal finger diameter drill-tube was standard for drilling royal sarcophagi, and that the internal length and width of a sarcophagus was obtained by centralizing the nearest whole number of drill-tube diameters, when just touching each other (Petrie 1883: 176, plate XIV, 13), leaving an adequate amount of stone after drilling around the perimeter to form the side and end walls.

The bottom of the curved mark probably represents a maximum initial penetration of the tubular drill, owing to adverse frictional forces. The experimental use of an 8-cm diameter drill-tube showed that frictional forces generated by the rotation of the tube at the flat-ended cutting face, and by used sand powder clogging the spaces between the core and the hole wall, increased the force required to turn the tube. However, this compressing of the product of the tubular drilling of stone inside the drill-tube, a dry, finely ground cohesive powder (Stocks 1986a: 27), allows it periodically, and vitally for the introduction of fresh sand, to be withdrawn from deep tubular holes in sarcophagi. Wet sand, or wet sand drying-out, not only prevents the introduction of new crystals to a drill-tube's cutting face, but prohibits the withdrawal of used sand from a deep hole in a heavy artefact (Stocks 1993: 600).

The experiments indicated that a three-worker team was required to drive an 11-cm diameter tube (Stocks 1986a: 28, bottom illustration). It is visualized that two drillers pushed and pulled a large bow, with the third member steadying a hemispherical stone drill-cap placing pressure on the drill's cutting face (*cf.* Davies 1943: II, plate LIII, depicting a second worker assisting the bow-driller to steady the bearing-cap; II, plate LIV, illustrating the stone weighted drilling tool for hollowing stone vessels). The drilling and sawing experiments suggest that a pressure of 1kg/sq. cm is optimum. Consequently, long stone-cutting saws were probably weighted with stones at each end of the blade. Experimental sawing indicated that inertia, exacerbated by the friction generated in a long, deep slot, needed two ancient workers to overcome it, one at each end of the saw (Stocks 1986a: 28, top illustration).

In Cheops' sarcophagus, all 44 perimeter holes were probably drilled first, followed by the removal of their cores by hammering a wedge of stone or metal into the side of the tubular slot nearest the now isolated central mass; this strategy protects the walls from damage. The central mass could now be weakened by a further 18 holes (FIGURE 2), instead of a possible maximum 64 central holes (108 altogether) all touching each other (*cf.* a porphyry vessel, Cairo Museum JE18758, its interior completely drilled by eight tubular holes — seven around the perimeter and one in the centre). The true number of holes in the central mass can never be known, but craftworkers always try to minimize unnecessary work. In the 18-hole proposition, their cores and interconnecting columns of stone are sufficiently isolated to allow them to be broken away by stone mauls, without damaging vibration being transmitted to the walls. The removal of a first level of stone, down to '8·4 inches', lets a drill-tube penetrate further, beginning, as before, with the perimeter holes. Between four and six levels would be required to reach the bottom, dependent on the lengths of the drill-tubes. The cusps left in the walls after drilling, and the broken off cores and columns on the bottom, were probably removed by dressing with flint chisels and punches. Smoothing was initially accomplished with coarse sandstone rubbers, followed by the application of the finely ground sand/stone/copper waste powders from the sawing and tubular drilling processes. Polishing was probable done with leather laps and mud.

(cu. cm/hour)

	experimental rates		**estimated ancient rates**	
	drilling	**sawing**	**drilling**	**sawing**
granite	2	5	12	30
calcite	30	75	180	450

TABLE 1. *Experimental and estimated ancient drilling and sawing rates in rose granite and calcite. The area of contact is greater for saws, and the reciprocating action for sawing is less tiring than converting the same action into rotary motion.*

Conclusions

The data in the preceding section can now be used in conjunction with the indicated ancient sawing and drilling rates, and the suggested consumption of materials, to determine the approximate expenditure of copper, sand and time for the manufacture of Cheops' sarcophagus.

My experimental and estimated ancient drilling and sawing rates are contained in TABLE 1.

Possibly, to save time, two two-worker teams sawed opposite sides, ends and top and bottom at the same time. Similarly, three three-worker teams had sufficient space simultaneously to drill the sarcophagus — a team at each end and one in the middle. The experimentally determined ratios of the weight of copper worn from saws and tubes to the weight of sawn or drilled granite and calcite are 1:0·9 and 1:12 respectively. In these tests, the usual amounts of sand consumed to saw or drill 1 cubic centimetre of granite and calcite were 250 g and 45 g respectively.

Using the 62-hole proposition for Cheops' sarcophagus, the intimated employment of two sawing and three drilling teams, the 5-mm saw and tube-wall thicknesses and calculations based upon the indicated ancient cutting rates, suggests the times for consecutively sawing and drilling to be 4 and 10 months respectively, with a further few months for dressing and polishing the sarcophagus and making its lid. (Naturally, the drilling times, and the consumed copper and sand, would proportionally be greater for 108 holes; the use of single two-worker and three-worker sawing and drilling teams would also increase the total manufacturing time). The calculated weight of copper lost from the saws (168 kg) and tubes (266 kg) amounts to 434 kg. The weights of sand used for sawing and drilling is estimated to be about 14·5 and 22·5 tonnes respectively, a total of 37 tonnes. The waste powdered product of sawing and drilling igneous stones, containing copper particles, may have been stored for later use as an abrasive for stone polishing, stone-bead drilling and for some blue and green faience glazes (Stocks 1986b: 17; 1989: 528; 1997: 180–81). In this connection, water with sand abrasive washes away the particles of copper worn from saws and drill-tubes, adversely affecting the powder's possible use for faience glazes.

The total weight of excavated stone was 3186 kg, but the weight of drilled stone, if using the proposed 62 holes, would be 242 kg. The ratio of the weight of drilled granite to the total weight of excavated granite is 242:3186 or 1:13, and the ratio for the weight of copper lost from the drill-tubes to the total weight of excavated granite is 266:3186 or 1:12. Expressed as the volume of copper lost to the volume of excavated stone the ratio is 1:40 (where copper's specific gravity is 8·94g/cu. cm, 3·3 times the specific gravity of granite). The efficiency of this method of safely hollowing stone sarcophagi is indicated by these favourable ratios.

The chiselling, adzing, scraping, sawing and drilling tests on soft limestone, calcite and granite reveal a significant difference between tool materials, employed techniques and the consumption of copper, sand and time for manufacturing sarcophagi made from these three types of stone. In particular, there was a steep rise in the use of copper, sand and time for making igneous stone sarcophagi, commencing in the Fourth Dynasty.

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Eventually, the king's officers were replaced by professional judges, drawn from the clergy, to pronounce sentence at the "portal-where-justice-is-given" (*rwt-dỉ-Mȝˁt*) in Ptolemaic temples. Indeed, who could be more able and willing to administer justice than the god himself, "the vizier of the feeble," who "does not take bribes from the guilty, and [never] says 'bring written evidence!' " (*Praise of Amun*, dating from Merenptah, nineteenth dynasty).

[*See also* Administration, *articles on* State Administration *and* Provincial Administration; Crime and Punishment; Family; Inheritance; Marriage and Divorce; Officials; Prices and Payment; Slaves; Tomb Robbery Papyri; Women; *and* Work Force.]

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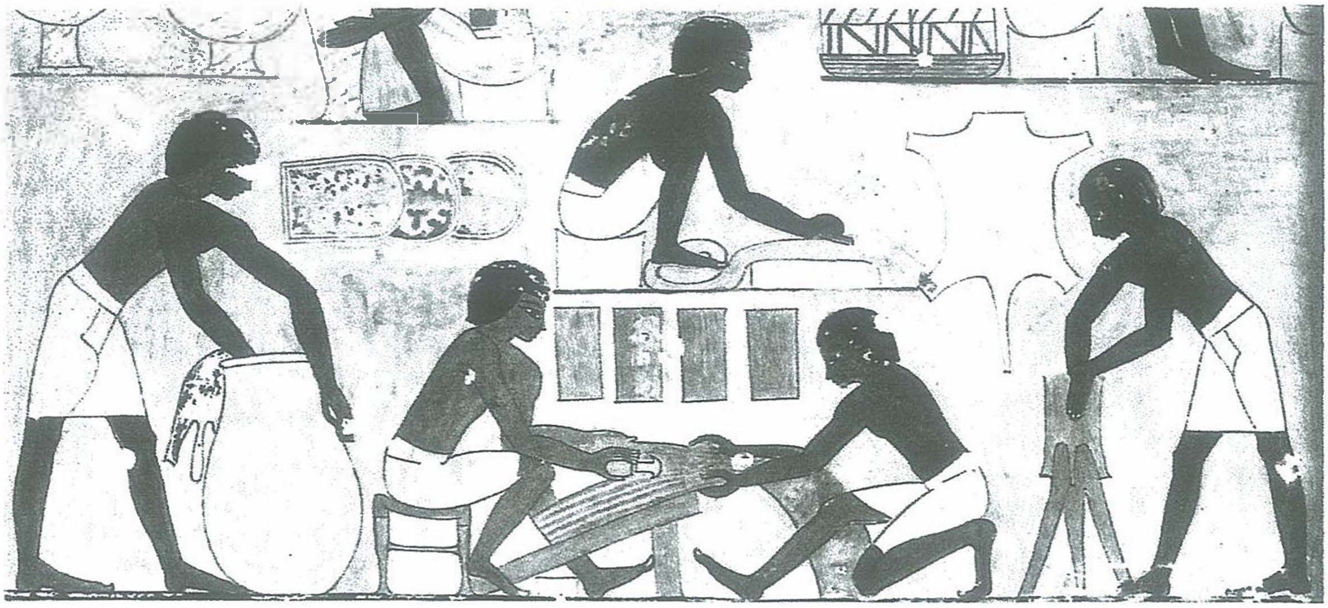
JEAN-MARIE KRUCHTEN

LEATHER. The first evidence in ancient Egypt for "leather" (*dḫr*) occurs in Neolithic graves of the Badarian (c.5500–4000 BCE) period. These Predynastic dead were provided with leather aprons and cloaks, occasionally decorated with painted geometric designs in black, blue, white, and yellow, as well as sandals, cosmetic bags, and cushions (their leather covers stuffed with vegetable matter). Leather, throughout Egypt's history, was manufactured mainly from the skins of calfs, gazelles, goats, and sheep. Predynastic leatherworkers tanned skins by drying, smoking, salt curing, and coating in ocherous earths. Sometimes skins were softened by the use of dung, fat, and urine; they were tanned by the use of oils and they were tawed with alum (any of a group of astringent mineral salts). Although a rather stiff leather, alumed goatskin sandals were found at Mostagedda and at Thebes in Upper Egypt. The seat of a stool from Tutankhamen's New Kingdom tomb was also of goatskin, but his sandals were of calfskin.

From a Predynastic tannery at Gebelein in Upper Egypt, pieces of leather were found to be treated by a liquor made from the pods of the acacia tree (*Acacia arabica*), also found there, that contained about 30 percent tannin. A scene in the New Kingdom tomb of the vizier Rekhmire at Thebes probably shows a leatherworker removing a skin from a similar tanning liquor. Before tanning, skins were stripped of hair and flesh by flint scrapers (later by metal scrapers) after a long soaking in brine; they were then steeped in clean water to remove the salt, dirt, and blood. The tanning process included one or more soakings in the tanning liquor. After tanning, hides were dyed red, yellow, or green. They were then stretched and dried over wooden trestles and smoothed with stones. Alum was basic to the finish, acting as a mordant for fixing dyes to leathers. The dyes used included kermes, a purple-red color made from dried female insect bodies



LEATHER. *Depiction of leatherworkers.* This is a copy of a painting in the eighteenth dynasty tomb of the vizier Rekhmire at Thebes. The workers soak and scrape the skins and make them pliable over a wooden horse. (The Metropolitan Museum of Art. [35.101.2])

(genus *Kermes* or *Coccus ilicis*), and madder, a red created from the roots of the madder plants *Rubia peregrina* and *Rubia tinctorium*. Yellow may have been obtained from the rind of the pomegranate (*Punica granatum*); green from a combination of the woad plant (*Isatis*) with yellow.

The production of footwear has accounted for many of the known leather artifacts. An example of a shoe developed from a sandal design was unearthed at Illahun, a twelfth dynasty workers' town in the Faiyum, although a cobbler's shop has not yet been discovered there. In the tomb of Rekhmire, wall scenes show workers cutting hides into sandal soles and straps with a semicircular bronze knife. This knife cut around a hide's circumference to make lengthy thongs, which were used for stitching leather; they were also twisted into ropes, particularly for ships' cordage. Leather or rawhide thongs were used to lash handles to adze and ax blades, and for making furniture joints. Other leather working tools included copper and bronze awls for piercing holes, horns for the enlargement of holes, and bone (later copper) needles and bodkins for sewing and assembling leather pieces. (Replica and reconstructed ancient tools perform well on both thick and thin leathers.) These tools and techniques produced leather goods for many purposes. Military personnel were supplied with leather footwear, loincloths, shields, body armor, quivers, and wrist guards. Chariots had floors of interlaced leather strips, as did stool and chair seats. Chariot wheel coverings, axle bearings, harnesses, and decorative bodywork were also of leather. Leather was also fashioned into funerary goods, bracelets, dagger sheaths, wall hangings, writing materials, box coverings, mirror cases, and clothing.

Leatherworking is depicted in private tombs that date from the fifth to the twenty-sixth dynasty at Giza, Saqqara, Deshasheh, Beni Hasan, and Thebes. Workshops were likely established near these cemeteries, since commissioned work by the wealthy conferred prestige and favor on highly skilled leatherworkers. An illustration in the fifth dynasty tomb of Ti at Saqqara depicts sandals being offered for sale. A sandalmaker's workshop is shown in the twelfth dynasty tomb of Amenemhet at Beni Hasan in Middle Egypt. One of this nomarch's titles, "Overseer of Horns, Hooves, Feathers, and Minerals," probably indicates a responsibility to collect leather taxes for the government. This, in turn, implies that all leather goods possessed recognized values. For example, the price of a pair of shoes during the New Kingdom equaled 1 to 2 *deben*, a standard weight in copper. The system of payment for work by the state, by high officials, and by the temples included leather goods, often leaving workers with surpluses that could be traded for necessities or other goods. A regular international trade in leatherwork is not certain, but in the eighteenth dynasty Theban tomb of Huy, viceroy of Nubia, and in the nineteenth dynasty temple of

Ramesses II at Beit el-Wali in Nubia, leather furniture and shields are shown being brought into Egypt as tribute.

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LEATHERWORKING. *See* Leather.

LEBANON, the northern Levantine region along the eastern Mediterranean coast that was an important source of coniferous woods (especially cedar), resins, wine, oil, and various finished goods for Egypt. The major coastal towns of ancient Lebanon (Akk., *labnanu,* Heb., *lĕbānôn*) developed around natural harbors and became wealthy through trade with the Mediterranean world and the Near East. Four narrow and roughly parallel north–south ecological zones (the coast and coastal plain; the Lebanon Mountains; the Biqaʿ Valley, and the Anti-Lebanon Mountains) encouraged the development of independent political entities, rather than a unified country. Lebanon's ports and towns were never a military threat to Egypt, whose interests in the region were largely economic and political. On occasion, however, Lebanese ports served as launching points for Egyptian military campaigns against enemies to the north and east.

Pharaonic Egypt's relations with Lebanon are historically fragmentary and based largely on textual sources. Because the principal Bronze Age and Iron Age coastal towns (Tyre, Sidon, Sarepta, Beirut, and Byblos) mostly lie under present-day cities, the excavation of Lebanon's ancient settlements is rarely possible. Byblos (today's Jebail) and Kumidu (Tell Kamid el-Loz, situated in the southern part of the Biqaʿ Valley) are the only two Bronze Age towns to have had significant excavation; Sarepta (today's Sarafand) is the one Iron Age coastal town.

Analyses of wood from the late Predynastic settlement at Maadi near Cairo indicated that Lebanese cedar had been imported into Egypt by the late fourth millennium BCE. The oldest inscribed Egyptian object found in Lebanon is a broken stone vessel from Byblos that contains the name of Khasekhemwy, the last king of the second dynasty (r. 2714–2687 BCE). This item was probably a gift to a Byblos ruler or temple; in the Bronze Age and Iron Age, Egyptian kings regularly sent gifts to the temples and political authorities of important Lebanese towns, as part of their effort to maintain favorable commercial and political ties.

Egypt's relations with Lebanon intensified during the Old Kingdom, when timbers of Lebanese cedar were imported into Egypt in considerable quantities, and a wealthy Egyptian state and its nobility wanted to acquire sometimes exotic goods. A fifth dynasty relief in the mortuary temple of Sahure at Abusir, for example, shows a Near Eastern bear and flask. Stone vessels, statuary, reliefs, and other large objects inscribed for fourth, fifth, and sixth dynasty kings and officials have been found at Byblos—whose principal goddess, Baalat Gebal, the Egyptians linked with their own goddess Hathor. In addition, an axhead inscribed with the name of Khufu was found at the mouth of the nearby Adonis River. The collapse of Egypt's Old Kingdom and the destruction of Byblos in the late third millennium BCE temporarily ended Egyptian activities on the Lebanese coast.

Egypt's contacts with Lebanon were restored in the eleventh dynasty and flourished once again in the twelfth. The *Story of Sinuhe* names Byblos as that Egyptian official's first stop, after he fled Egypt following the death of Amenemhet I. At Byblos, during the twelfth and thirteenth dynasties, local officials employed both Egyptian writing and political titles. Egyptian and Egyptianized objects were numerous in that period at Byblos; outstanding objects include an obsidian jar inscribed with the name of Amenemhet III and an obsidian box with the name of Amenemhet IV. A small diorite sphinx inscribed with the cartouche of Amenemhet IV was found during some modern construction work in Beirut, and several Lebanese coastal cities (including Byblos and Tyre) were mentioned in the Egyptian Execration Texts.

Egyptian–Lebanese connections remained close well into the late eighteenth century BCE. A relief fragment depicting the Byblos mayor Yantin, along with a cartouche of Neferhotpe I (r. 1747–1736 BCE), comes from that site, while a fragmentary statue of Khaneferre Sobekhotpe IV (r. 1734–1725 BCE) was discovered at Tell Hizzin in the northern Biqaʿ Valley. Archaeological evidence for relations during the latter half of Egypt's Second Intermediate Period is meager, but the prominent mention in the Kamose Stela at Karnak of three hundred ships of cedar

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REGINA HOLZL

STONEWORKING. In ancient Egypt, stone was used for building purposes as well as for utilitarian and revered objects; almost all kinds of available stone were used, both hard and soft. The relative hardness of stone can be described and compared to the Hardness Scale of Minerals devised by Friederich Mohs (1773–1839). Mohs arranged them in ten ascending degrees, from the softest (1, talc) to the hardest (10, diamond), with the rest listed between (2, gypsum; 3, calcite; 4, fluorite; 5, apatite; 6, orthoclase; 7, quartz; 8, topaz; and 9, corundum).

Two important tools for working hard stone (*rwdt*) were the tubular drill and the straight-edged saw, both of copper (*bỉȝ*) in use with a quartz sand (*šʿy*) abrasive. Before c.3500 BCE, some stones were drilled by the common marsh reed (*Phragmites communis*), rotated by a bow with dry quartz sand, but after that date, the Naqada II (c.3500–3150 BCE) stoneworker (*ḥm-ỉnr*) copied the reed's tubular shape in copper and, later in dynastic times, in bronze. The reed effectively drilled hard limestone (*ỉnr ḥḏ;* Mohs 3–5), calcite (often mistermed "Egyptian alabaster" or "alabaster," *šs;* Mohs 3–4), and marble (Mohs 3–5). Although pure calcite and pure limestone (both calcium carbonate) are usually of Mohs 3 hardness, variations in composition and/or mineral inclusions cause some varieties (particularly limestone which is usually combined with magnesium carbonate) to be harder—ranging between Mohs 3 and 5; modern-day drilling and cutting tests indicate this range for Egyptian calcite, limestone, and marble. Holes in harder stone—such as basalt (*bḫnw;* Mohs 7–8)—were made in ancient times by grinding with handheld borers of sandstone or borers of other stone material used with a quartz sand abrasive, continually twisted clockwise and counterclockwise. Perforations for stone beads were often made by similarly twisting borers of flint (*ds*) back and forth. [*See* Calcite *and* Limestone.]

The copper tube (which in use leaves a removable core) was sometimes driven by a bow, its string twisted around a tightly fitted wooden shaft and its top end rotated in a stone bearing-cap. For example, the perforated lug handles on Naqada II hard-stone vessels show striated tapered holes, typical of this drilling technique. Bow-driven copper tubes of 110 millimeters (6 royal fingers or 4.25 inches) in diameter were used to drill rows of adjacent touching holes in cutting out the center of Khufu's (Cheops') granite (*mȝṯ*) sarcophagus that is still inside the Great Pyramid at Giza. As long ago as 1883, W. M. Flinders Petrie discussed the dimensions of tubular-shaped holes and saw cuts in his *The Pyramids and Temples of Gizeh.*

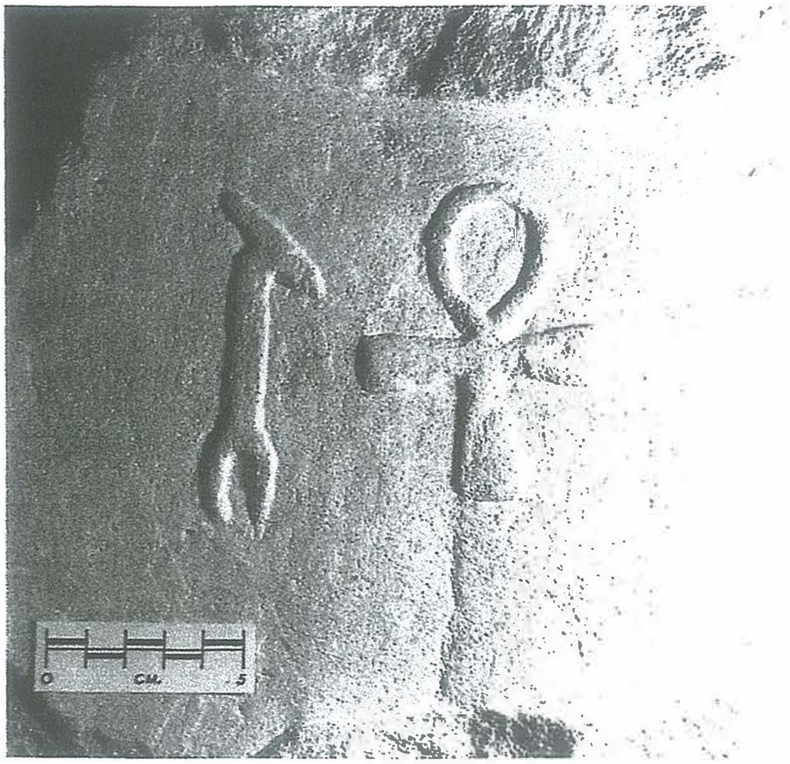
Copper tubes varied from approximately 6 to 125 millimeters (0.25 to 5 inches) in diameter, with wall thicknesses of 1 to 5 millimeters (less than one-quarter inch), similar to saw-blade thicknesses. Small diameter, thin-walled tubes were created from beaten sheet copper, while large diameter, thick-walled tubes were probably cast in vertical sand molds. The weighted, straight-edged stone-cutting saw, cast horizontally (up to 2.5 meters [8 feet] in length with a thickness of about 5 millimeters), was employed to cut hard-stone architectural blocks and to roughly shape sculpture, beginning in the first dynasty (c.3050–2850 BCE). From the third dynasty onward (2687–2632 BCE), it was used to cut calcite and harder stone sarcophagi to size.

Present-day tests on granite, limestone, and calcite by drilling and sawing resulted in ratios of the weight of copper worn off the tools to the weight of the abraded stone removed—these were 1:0.9, 1:8, and 1:12, respectively; the usual consumption of sand and the amount of time for drilling or sawing 1 cubic centimeter of those stones were 250, 50, and 45 grams and 40, 5, and 2 minutes. That data allowed for some calculation of the approximate sand and copper consumption, as well as the manufacturing time, for a specific artifact. For example, the sawing, drilling, and finishing of Khufu's granite sarcophagus required about 37 metric tons (tonnes) of sand, 430 kilograms of copper, and 21 months of man-hour time to make. The finely ground resulting waste powders contained minute quartz, stone, and copper particles, quite dangerous to health (causing silicosis). In present-day tests, limestone and calcite powders were used to make faience cores, and granite powders created blue glazes that were similar to some ancient faience (*tḥnt*). The waste powders were also probably used to make a paste for drilling varieties of quartz (Mohs 7)—agate, amethyst, carnelian—and other stones for beads with a pointed,

STONEWORKING. Figure 1. *Mallet used in stoneworking, from Deir el-Bahri.* (University of Pennsylvania Museum, Philadelphia. Object # E 2434)

bow-driven copper drill. However, eighteenth and nineteenth dynasty (c.1569–1201 BCE) bead drillers at Thebes, Upper Egypt, each spun up to five bronze drills simultaneously with one bow. Present-day experiments confirmed the feasibility of that mass-production technique.

Vessels of breccia, diorite, basalt, porphyry, schist, and serpentine were made in large number in Naqada II times, because of the introduction of a combined drilling and boring tool; the vessels were always shaped before they were hollowed. Representations from dynastic times depicted a stone-weighted wooden shaft, angled at the top for a handle. The shaft was crafted from a forked branch, with its main stem cut away above the fork. A copper tube was forceably fitted onto the end of the shaft; the tool was moved back and forth, clockwise and counterclockwise, by wrist action. Several ever-widening tubes were worked



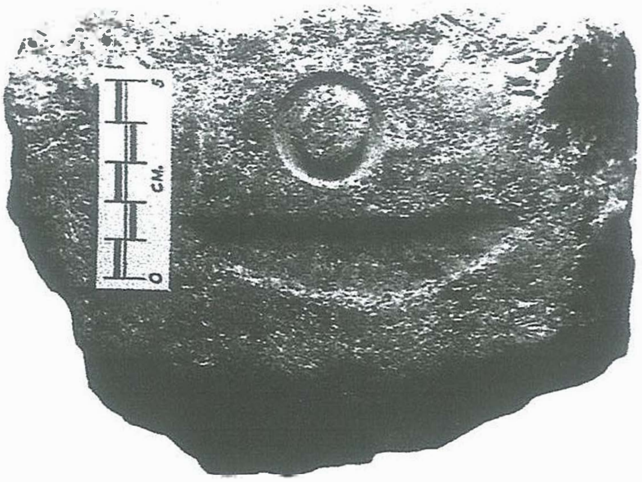
STONEWORKING. Figure 2. *Test bas relief in soft limestone, made by mallet-driven copper chisels.* The edges were scraped by flint tools. (Courtesy Denys A. Stocks)

at the same spot, to weaken the central mass safely, although in a large vessel adjacent holes were drilled around the mouth's perimeter to create the perforation effect. For a bulbous vessel, a forked shaft lashed to the main shaft drove a series of ever-larger figure eight-shaped stone borers, which widened the original drill hole. Vessels of gypsum (Mohs 2) were bored out by crescent-shaped flints that were on forked shafts, as were inverted, truncated-cone borers that shaped such gypsum vessels' mouths. Domestic trading in, for example, stone vessels, palettes, and flint knives, increased from Naqada II to Naqada III (c.3200–3050 BCE). In particular, Upper and Lower Egyptian Predynastic and later dynastic stone vessels were valuable trade objects, used in exchange for essential foreign raw materials, such as cedar wood from Lebanon.

Most stone types, including soft limestone and hard sandstone for building were quarried using picks and axes of granite, quartzite, chert, and flint. Very hard stone, however, such as granite, was detached by pounding with handheld dolerite balls. Conversely, the curved parts of sculptures were gently bruised into shape with hafted stone mauls. Limestone tomb walls were shaped and smoothed with flint and metal chisels and adzes; flat-tapered copper and/or bronze chisels fashioned soft limestone building blocks after their rough shaping by stone tools. Present-day tests revealed that the copper or bronze chisel (*mḏȝt*) and adze (*msḫtyw*) were only effective for cutting the softer stones (Mohs 3 and 2)—limestone, red sandstone, and gypsum (Figure 2)—and so bas-reliefs and incised hieroglyphs in all other stones, including true calcite (a mineral with hexagonal crystallization), were necessarily worked by disposable (throw-away) flint tools. (Flint, although hard [Mohs 7], is brittle; it chips or flakes along a grain or cleavage line.) The shaping of hard-stone artifacts, such as vessels, and the cutting of hieroglyphs, was accomplished by driving rudimentary flint punches and chisels into the stone, thus chipping away small pieces (Figure 3). The tools suffered gradual destruction.

Occasionally, the hieroglyphs in harder stone were made smooth with stone grinders; but the hieroglyphs in softer stones, such as calcite and schist, were frequently scraped to a sharp edge with flint tools. After grinding, stone surfaces were polished with waste-drilling powders; flat surfaces were tested by three equal-length wooden rods. Two of the rods were joined by a length of string attached at the top of each. These were stood apart on the surface, with the string pulled taut. The third rod, held against the string and shifted along the surface, would then indicate high spots needing further work (marked by a finger coated in red ocher).

Stoneworkers lived in communities near the sites of



STONEWORKING. Figure 3. *The biliteral sign* nb *cut into granite by test flint punches and chisels*. The sign was polished by sandstone grinders and drilling powders of the waste material.

royal building and manufacture, for example, at Illahun in the Faiyum, Deir el-Medina at Thebes, and at Tell el-Amarna and Giza. Others toiled in palace, house, and temple workshops.

[*See also* Technology and Engineering; Tools; *and* Vessels.]

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DENYS A. STOCKS

STORAGE. Egypt's economy depended on collecting and redistributing grain, manufactured goods, and raw materials. Storage, therefore, played an integral role in the smooth functioning of the major institutions of state and temple. Palace, temples, and individuals all maintained "granaries" (*šnwt*) for food. Palaces and temples also established treasuries, each called the "House of Silver," that were intended to stockpile valuables. Workshops within a palace or temple were called the "House of the Plow"; there workers manufactured and stored finished goods including pottery, wooden furniture or even bread. The bureaucracies of the granary, treasury, and workshop were interconnected, although their relationships and the relative power of each of the bureaucracies shifted in response to the king's need to maintain control over Egypt's resources.

The Archaic Period and Old Kingdom. In the earliest periods, granaries are attested from archaeological examples, such as those excavated at Merimda-Beni Salama during the Badarian culture (c.5000 BCE), while treasuries are known from seals of officials who worked there as early as the first dynasty (c.3050–2825 BCE). Workshops located in the "House of the Plow" are represented on tomb walls by the fifth dynasty (c.2513–2374 BCE), though various kinds of industrial sites, such as those for manufacturing pottery and flint tools have been associated with earlier prehistoric periods. It is unclear when the "House of the Plow" was established to maintain them.

Models of granaries were found in tombs of the first two dynasties. They were shaped like cones on a round base or were domed with an opening for filling and emptying. The models resemble real granaries found throughout Egyptian history. Actual granaries were sometimes associated with tombs during this time, and they exhibit the same design as models, incorporating mud-brick vaulting coated with clay. Relief sculpture of granaries in tombs of the third and fourth dynasties show them filled with grain and fruit. By the sixth dynasty, granaries were represented alongside storage for manufactured goods. The proximity of food and manufactured items in those reliefs suggests a connection between granaries and the "House of the Plow" in this period.

The granary, however, had it's own bureaucracy in the Old Kingdom, headed by an overseer; scribes, inspectors, and chiefs were also assigned to work in the granary. Peh-

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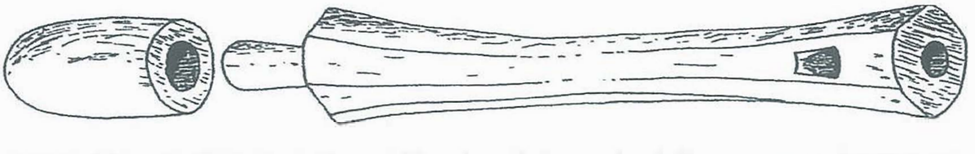
AIDAN DODSON

TOOLS. About 3500 BCE, Egyptian metalworkers discovered the way to smelt copper ore and cast copper into sizeable and useful metal tools. At first, small adze blades, chisels, and ax heads were cast into open molds made in damp sand. Such metal tools—the chisel (*mḏȝt*) and the adze (*msḫtyw*) evolved from earlier stone tools that had been driven by rudimentary mallets; or they were swung by hand in glancing blows against materials. The metal ax (*mibt*) and knife (*ds*) imitated earlier stone shapes. Sand molds are only used once, but at Illahun, a twelfth dynasty (c.1991–1786 BCE) manufacturing town in the Faiyum of Middle Egypt, workers cast chisels, knives, and ax heads in reusable open pottery molds. Such fired ceramic molds allowed the mass production of metal castings. The use of closed pottery and stone molds, in two halves, plus the lost-wax (*ciré pèrdue*) process created small, solid castings; large, lost-wax molds, with clay cores, produced hollow castings that consumed relatively less metal. Open wooden molds were used for making mud bricks; pottery molds were for shaping faience cores; and clay and limestone molds were for casting glass in dynastic times.

From Neolithic times or earlier, fire was created by bow-drilling—a long, waisted, hardwood drill-stick was spun by a bow (similar to a hunting bow) in a hole previously drilled into a softwood block by an auger. By the twelfth dynasty, a waisted drill-stock force-fitted with a short replaceable stick superseded the long drill-stick. An ejection hole in the stock let a worker remove worn sticks (Figure 1). Waisted drill-shafts allowed a stretched bowstring to engage on a wider diameter, automatically increasing its grip.

Predynastic and dynastic smelting furnaces were fired up and obtained their air through blowpipes. Between two and six blowpipe workers were illustrated in tomb scenes of the fifth dynasty (c.2513–2374 BCE) to the eighteenth dynasty (c.1569–1315 BCE). The furnace blowpipe, supplied with a nozzle of dried clay, was fashioned from the common marsh reed (*Phragmites communis*); it measured about 1 meter (3 feet) in length. Jewelers' blowpipes were about half as long. Reed stems were prepared by jabbing a thinner sharpened reed or stick through a reed's leaf-joint partitions, to open all the previously separate hollow sections. Present-day blowpipe experiments determined that four to six workers could supply enough air to melt up to 1.3 kilograms of copper or bronze in one crucible of fired clay and fused ash. Crucibles were also employed for melting the constituents of glass. In the sixth dynasty tomb of Mereruka at Saqqara, workers were shown manipulating crucibles with flat stones or pottery pads, but workers in the eighteenth dynasty tomb of the vizier Rekhmire held crucibles with withies (two freshly cut sticks). Foot-operated bellows were depicted in eighteenth dynasty Theban tombs. These consisted of two adjacently placed, flat-bottomed circular pottery bowls, each tightly fitted at the rim with a loose leather diaphragm. A worker alternately trod on one diaphragm and simultaneously pulled up the other with an attached string. A natural walking rhythm ensured a steady supply of air through attached reed tubes. Such large copper and bronze tools as stone-cutting saws needed the concurrent operation of several furnaces to melt sufficient metal for a single casting. Other cast metals were gold, silver, and lead.

Copper, bronze, gold, and silver plates—probably open cast to the thinnest dimension possible, 5 millimeters—were then beaten when cold into thinner sheets on a stone anvil set on a wooden block that was buried in the earth. The metalworker used a selection of hand-held spherical and hemispherical stone hammers that varied in size and



TOOLS. Figure 1. *Kahun bow-driven drill stock, with its wooden drill cap.* A tool can be removed by pushing a short stick into the ejection hole. (Drawn from Manchester Museum Catalogue number 23. Courtesy Denys A. Stocks) weight. Gold leaf was beaten thin between skins that allowed a flexibility for application; and raised reliefs in metal (*repoussé*) were achieved with chisels and punches of bone, wood, stone, and metal.

Some long flat-edged, copper stone-cutting saws—used with quartz sand abrasive for cutting hard stone statuary, sarcophagi, and blocks—were cast and used at a 5 millimeter thickness, but others were beaten thinner. For cutting wood and soft limestone, the edges of thin copper saws were given serrations, by notching them on a hard, sharp object—probably inspired by the Mesolithic serrated flint sickles for cutting reeds and other stems in use before the introduction of copper casting (reconstructed stone-cutting saws and replica wood-cutting saws efficiently cut these materials). In Middle Kingdom tomb scenes, workers saw planks off timber lashed to sturdy posts that are partially buried in the ground. A metal or stone wedge probably kept a cut open in the wood. Inserted into the lashing is a short wooden rod with a stone counterweight hanging on its free end (tests with reconstructed equipment showed that the rod acts like a tourniquet, quickly tightening or loosening the lashing).

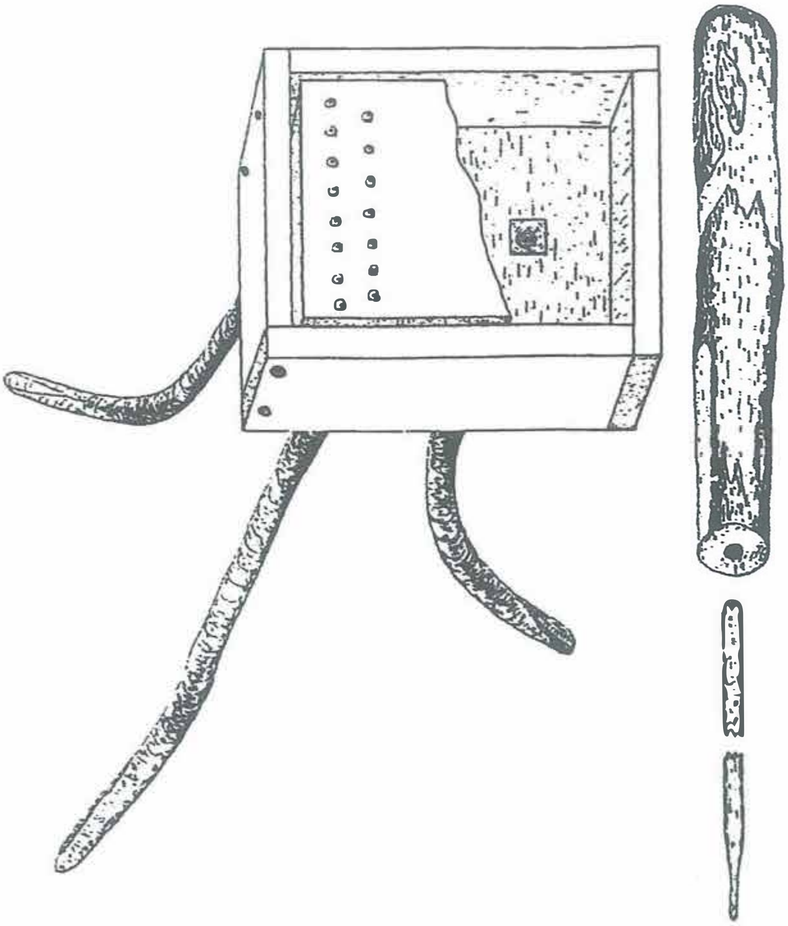
Spherical and hemispherical hammers were also used to shape gold and silver vessels, which were placed upside down on a tripod anvil. Smooth agate burnishers and leather balls were used to polish the finished vessels. The anvil consisted of a forked branch, set at an angle into the ground, with a long wooden or metal rod passing easily through an upward-slanting hole drilled into the upper part of the branch. Such a reconstructed anvil demonstrated that not only did the projecting rod function as the third leg of the tripod but also its length was adjustable for work on both large and small vessels (by sliding it through the hole). Weight on the anvil "locks" it into position.

Cast copper and bronze tools were shaped cold for maximum hardness; however, excessive hammering causes cracking. The Egyptians eventually found that some tools needed to be annealed—by heating and then cooling several times for multiple hammerings. The copper adze was developed from the slim, narrow Predynastic blade to the wider one of dynastic times. Some blades were cast with lugs, to aid their fastening by leather thong to wooden handles; others had a distinctive neck. Adze blades were used for skimming and shaping wood or soft limestone surfaces. Wooden mallets drove flat-tapered and crosscut-tapered chisels, but these were strongest in cross section and were sometimes fitted with wooden handles; they were used with mallets to cut and lever wood from deep mortises. Chisels were often held for carving wooden sculpture, and intricate carving could be achieved by flint as well as by metal tools. The shape of metal ax heads changed with time, but the ax's cutting edge—used by carpenters and boat builders—was rounded in form, for splitting wood along the grain and chopping across the grain. The ax was sometimes supplied with lugs or a hole, for fastening the head to its wooden handle. Tool handles were made from branches that had the bark removed by flint scrapers and the surfaces smoothed by sandstone blocks.

TOOLS. Figure 2. *A reconstructed bow-driven drill shaft, fitted with its copper tube.* (Courtesy Denys A. Stocks)

Leatherworkers since Paleolithic times had used flint scrapers and flint knives for preparing and cutting hides; these tools were also used in Egypt for cutting and splitting reeds, papyrus, and other plant stems and were developed into metal scrapers and knives. The New Kingdom semicircular bronze leather-cutting knife was fitted into a wooden handle, and copper and bronze awls, bodkins, and needles were made to stitch leather pieces together (previously, they were made from bone or ivory).

Stone tools—for working calcite and harder stone vessels, for statuary, sarcophagi, palettes, stelae, and the cutting of bas reliefs and incised hieroglyphs—included chisels, punches, and scrapers of flint and hafted stone mauls. Some stones were shaped and smoothed by stone grinders—probably by a paste made from finely ground waste-drilling powders, and possibly a mud polishing medium,

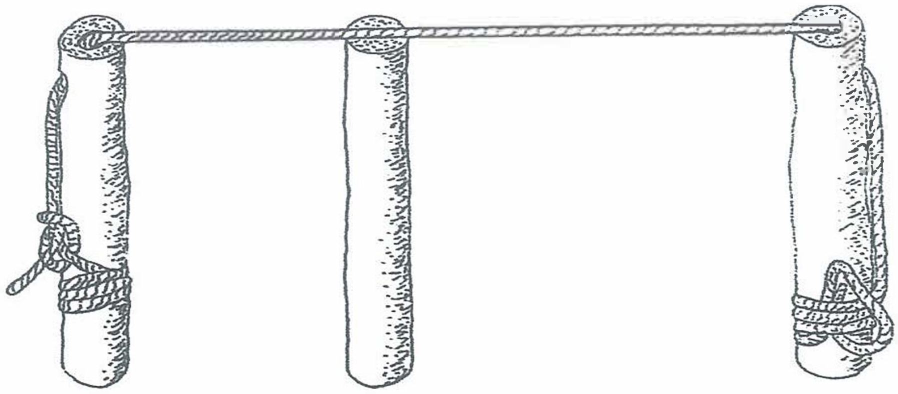


TOOLS. Figure 3. *(Left) A reconstructed three-legged New Kingdom drilling table, showing the probable way in which beads were located for drilling. (Right) A reconstructed stick handle and bronze drill rod.* (Courtesy Denys A. Stocks)

applied with leather balls. Picks and axes of granite, quartzite, chert, and flint were use to quarry the softer stones, like limestone and sandstone; dolerite pounders were used for detaching harder stone for construction, statuary, and obelisks. Flint adzes, chisels, and scrapers were used alongside copper and bronze adzes and chisels for smoothing and carving reliefs in soft limestone tomb walls, blocks, and other objects.

Egyptian workers possessed five types of bow-driven tools, including (1) the fire drill (*ḏ3*); (2) copper and bronze tubular drills (Figure 2); (3) copper and bronze single-bead drills; (4) bronze drill-rods for simultaneously perforating several stone beads; and (5) a wooden drill-stock that drove interchangeable tools, such as the fire stick or the metal auger (used to drill stringing holes in furniture and peg [dowel] holes for furniture joints). The bow-driven augers probably did not drill large holes in ships' timbers; instead, a copper auger attached to a handle was used, which gave great twisting power to its cutting edges.

For drilling the suspension lugs carved on stone vessels, statuary, sarcophagi, and their lids, bow-driven tubes were employed with dry quartz sand abrasive. These were formed from thin sheet copper for small tubes, but the large ones were probably cast in vertical molds. Reed tubes, rotated on sand, were used to drill calcite and hard limestone vessels before about 3500 BCE. After that date, Predynastic workers copied the hollow reed's shape in copper, and later, bronze. A stone vessel's interior was widened by a forked shaft lashed to a weighted shaft that drove circular, figure-eight, and conical-shaped stone borers, employing quartz sand as an abrasive. For boring soft gypsum, crescent-shaped flints were also driven by forked shafts. The single-bead drill was fitted with a waisted shaft, driven by a small bow; a stone drill-cap exerted pressure. Holes were begun with flint borers, exclusively used for perforation before the metal drills were employed. In Thebes, two-to-five bronze drill-rods were rotated, each in a hole drilled into the bottom of a stick handle; the drills were held in a straight line by an operator's free hand and simultaneously spun by a long bow. The beads were probably set into a mud block that rested in a hollow-topped, three-legged table (Figure 3). (Reconstructed drilling equipment has shown that the change to



TOOLS. Figure 4. *A reconstructed surface-testing tool, consisting of two outer rods, taut string, and the third rod for revealing surface inaccuracies.* (Courtesy Denys A. Stocks)

mass-production drilling decreased perforation times for 10 millimeter-diameter amethyst beads from five hours to about one hour per bead.) Stone beads were polished by rubbing them along grooves in a wooden block filled with abrasive paste. Bow strings—or ropes if driving large-diameter tubes—were manufactured from halfa grass, flax fiber, woven linen, palm fiber, or papyrus.

For stone architecture, workers employed three vitally important tools for verifying horizontal and vertical planes and surface flatness: (1) An A-shaped wooden frame, for horizontal planes had originally been calibrated by making the bottom of the two legs just touch standing water—the only true horizontal in nature. The horizontal crosspiece was then marked where a plumb line, hung from the A's apex, passed it. (2) A vertical plane was checked by a wooden tool made from two accurately matched short pieces that were fastened at right angles (one above the other) to a longer, vertical piece; a freely hanging plumb line then just touched the end of both horizontal pieces when the plane was truly vertical. Tests with a modern spirit level found replicas of these to be accurate. (3) A stone surface-testing tool consisted of three wooden rods, accurately matched in length; two rods stood upright on the stone surface were joined at the top by a string, pulled taut; the third rod, when held against the string and shifted along the surface showed any unevenness (Figure 4). Replica rods can reveal surface inaccuracies as small as 0.25 millimeter (0.01 inch) along a length of 1.25 meters (4 feet) and therefore over an area of 1.25 meters squared (16 square feet). The joined rods, used as an inside caliper, may have verified parallelism between the end joints of blocks as the fitting progressed but before sliding them into position on gypsum mortar. Other important building tools included the wooden square, the lever, the roller, the plasterer's float, the cubit measure, a sledge for moving blocks, as well as measuring cords and leveling lines.

[*See also* Stoneworking; *and* Technology and Engineering.]

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DENYS A. STOCKS

TRADE AND MARKETS. Ancient Egypt was basically a "supply state." Products for consumption were delivered to state or temple institutions, which in turn distributed food supplies and other goods to the population. Allocation was based on a fair assessment of each person's requirements. People received as much as they needed. Surplus could be traded at local markets, a system which helped fill gaps in the flow of supply.

Trade among regions was always conducted by institutions, which bartered with the surplus from their own production. Merchants worked for these institutions, playing the role of agents in the exchange. Their task was to exchange the surplus of the institution they represented for as many valuable goods as possible. Generally speaking, merchants were therefore not working for their own personal profit. Merchants who worked for their own gain existed in ancient Egypt only during the New Kingdom.

Market Trade. The original and oldest form of trade is market trading in the form of barter. Many Old King-

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Testing ancient Egyptian granite-working methods in Aswan, Upper Egypt

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Rose granite was a favoured, but difficult, stone to work in ancient Egypt. Recent sawing, drilling and cutting tests of the granite in Aswan suggest how exacting were those tasks for craftworkers.

Key-words: granite, stone-working, Egypt, Aswan

The shaping of igneous stones by ancient Egyptian artisans into building blocks, statuary, sarcophagi and obelisks, many of them decorated with deeply cut hieroglyphs and reliefs, has engendered an admiration for such highly skilled work in hard stone. Rose granite (hardness Mohs 7), in use for all of these objects, was obtained from Aswan, Upper Egypt. This coarse-grained stone is composed mainly of quartz, mica and pinkish feldspar, the latter mineral being slightly softer than the quartz and widely distributed within the stone's matrix.

Three important techniques for working the granite were sawing, tubular drilling and relief cutting. The copper stone-cutting saw was employed for shaping hard stone blocks and sarcophagi (e.g. the basalt paving blocks at the Great Pyramid, Giza). The copper stone-cutting tubular drill (Stocks 1993: figure 1a) hollowed stone vessels (e.g. a porphyry vessel, Cairo Museum JE18758) and the interiors of stone sarcophagi (e.g. Khufu's granite sarcophagus at Giza). The cutting of stone is exemplified by the hieroglyphs incised into a rose granite column, British Museum EA1123.

In March 1999, an opportunity arose to saw, drill and cut the granite at a quarry located in Aswan. I received the able assistance of several Egyptian quarry workers to operate a reconstructed 1·8-m long copper saw and a reconstructed 8-cm diameter copper drill-tube, which I had taken to Egypt with a large driving bow. These sawing and drilling experiments were undertaken to test two theoretical propositions, first suggested by me (Stocks 1986a: 28, top and bottom illustrations), that two- and three-worker teams were required to drive large ancient saws and tubular drills respectively. I believe that these Aswan tests on the rose granite are the first to be carried out with reconstructed tools driven by teams of Egyptian stoneworkers.

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There is archaeological evidence that ancient copper saws and tubular drills were used with sand abrasive from the Third Dynasty (Petrie 1883: 174-5; Reisner 1931: 180; Lucas & Harris 1962: 74). Each Aswan tool used sand as the cutting abrasive.

The experimental cutting of a hieroglyph into a granite block in Aswan, with flint chisels and punches, allowed comparisons with the flint tools used in the Manchester tests, and elsewhere (Zuber 1956: 180, figures 18–20; Stocks 1986b: 27–9; 1988: II, 262–4, plate XXIV, b), and also with similar tools made from Egyptian chert (Mohs 7), a flint-like stone also thought to have been in use for cutting stones in ancient times.

The Aswan sawing experiments

The unused 1·8-m long copper saw blade, stood on its edge, measured 15 cm in depth, 6 mm in thickness and weighed 14·5 kg. Before my arrival in Aswan, the quarry workers had mistakenly fitted a heavy wooden frame to this saw blade, as well as notching it numerous times along the cutting edge with an electric abrasive wheel. Nevertheless, for comparison with a completely flat edge acting on dry sand abrasive, it was decided to test the notched edge with very wet, fluid sand along a granite block's width of 75 cm, its surface initially pounded flat along the line of sawing.

Two workers pushed and pulled the saw from opposite sides of the block. The blade rocked from side to side during each forward and backward movement, creating a V-shaped slot. At a depth of 8 cm, the V's cross-sectional shape measured 2·5 cm at the top and 6 mm at the bottom. This V-shaped slot is similar to two partially sawn slots seen in Djedefre's IVth Dynasty rose granite sarcophagus in the Cairo Museum (JE54938). The bottoms of these slots are laterally rounded, a further consequence of the rocking action of the ancient saw blade, which itself would have assumed a laterally rounded shape along its cutting edge. These phenomena also occurred in the dry sand sawing experiment.

Parallel, rough-edged striations of varying depths and widths, similar to those seen in ancient stone objects (e.g. Djedefre's sarcophagus), were visible on the sides and the bottom of the slot, and upon the saw's individual flat edges between the notches. There was extensive pitting to the sides of the saw, also seen in the subsequent dry sawing test. In both the wet and dry tests, the extra granite abraded to form each V-shape was disregarded when calculating the cutting rate. The wet sand sawing results are contained in TABLE 1. It was noticeable that the sand had to be kept fluid; drying-out sand rapidly increased an already significant effort to move the saw. The used sand powder slurry poured over each end of the slot, its copper particle content from the saw largely washed away into the ground below.

For the tests with the dry, but fluid, sand abrasive, I removed the wooden frame and reversed the blade to allow the completely flat top edge to operate on the stone; the granite block's width at the point of sawing was 95 cm. The blade was now weighted with four stones (FIGURE 1), two tied on to each end of the blade; these four stones, weighing 32 kg, also acted as handles for the sawyers (FIGURE 2). The saw's total weight of 45 kg placed a load of approximately 1kg/sq. cm upon the blade's edge in contact with the granite.

As before, similar parallel striations were visible on the sides and the bottom of the slot, and upon the saw's continuous edge. The angular crystals embedded into the edge and striated the stone under the blade and along the saw-slot's walls, sometimes causing new striations, at other times reinstating old ones, as the blade moved backwards and forwards along the stone.

	slot depth	slot length	time taken (hours)	saw depth lost	volume (cu.cm) of lost copper	weight (gm) of lost copper	volume (cu. cm) of sawn stone	weight (gm) of sawn stone	cutting rate (cu cm/ hour)	saw stroke length	ratio 1	ratio 2	ratio 3
wet sand	8 cm	75 cm	30	3·2 cm	170	1520	360	972	12	90 cm	1:2	1:0·6	1:2·5
dry sand	3 cm	95 cm	14	7·5 mm	52	463	170	459	12	115 cm	1:3·3	1:1	1:4

TABLE 1. *The data obtained from the sawing of rose granite with a copper saw separately in use with wet and dry sand abrasive. The specific gravities of granite and copper are 2·7 g/cu. cm and 8·94 g/cu. cm respectively.*

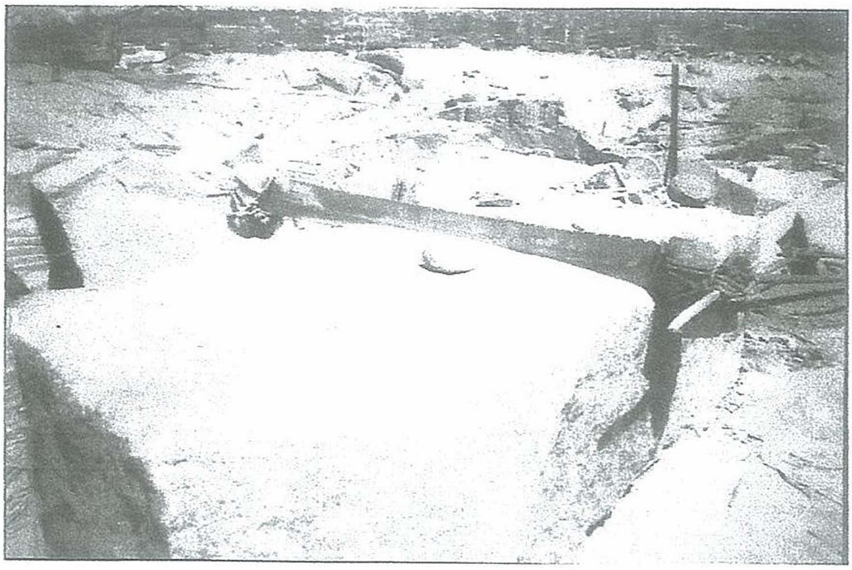

FIGURE 1. *The flat-edged, stone-weighted copper saw.*

FIGURE 2. *Egyptian workers drilling rose granite, with a flat-ended copper tube and dry sand abrasive. Two workers are using the stone-weighted saw in the background.*

The dry sand sawing results are also contained in TABLE 1. The rate of cutting was just over 12 cu. cm/hour, slightly better than the wet abrasive result. It was noticeable that the effort to reciprocate the saw using the dry sand was far easier than for the wet sand abrasive. The used dry sand powder, grey in colour, poured over each end of the slot, its copper content intact.

In TABLE 1, the three ratios expressing the volumes, weights and depths of the copper worn off the saw (separately with the wet and dry sand abrasive) to the volumes, weights and depths of the sawn granite are recorded as 1, 2 and 3 respectively. The ratios obtained from sawing with the flat-edged blade and dry sand show a distinct improvement to the ratios achieved with the notched edge and wet sand.

The granite drilling experiment

The tubular drilling of a rose granite block required the assembly of the four component parts of the drilling equipment: the flat-ended 8-cm diameter copper tube, the round wooden drill-

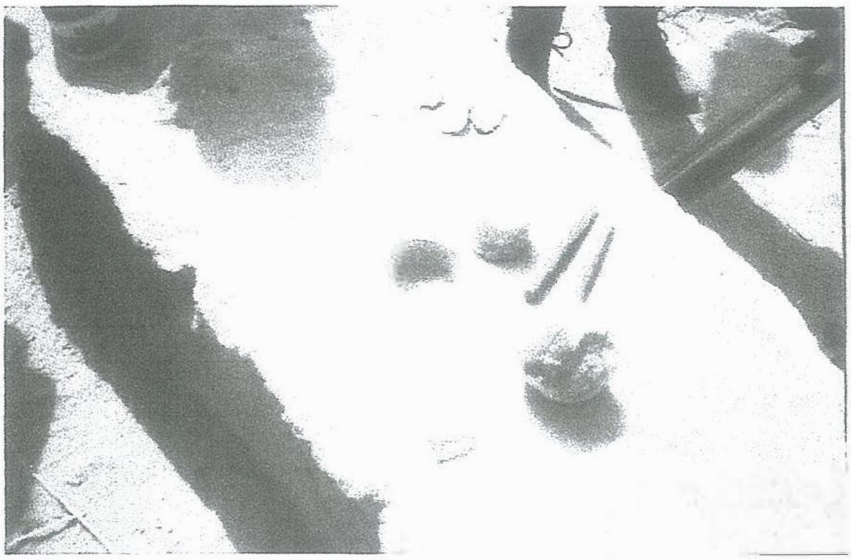

FIGURE 3. *The granite core and the chisels used to remove it from the tubular-shaped hole.*

shaft partly force-fitted into it, the driving bow and rope, and a capstone bearing in which to rotate the upper end of the drill-shaft. The capstone took one hour to shape and hollow, using flint chisels and punches, from locally obtained hard sandstone. The top of the shaft was carved into a cone, with a rounded top; previous drilling experience demonstrated reduced friction if the top of the cone rotated in the apex of the bearing. This was lubricated with grease, in place of the likely ancient tallow. Preliminary tests in Manchester indicated that a very stiff bow-shaft was needed to place sufficient tension on a 1·3-cm thick bow-rope, necessary to prevent slippage on the wooden drill-shaft. The bow-shaft was made from a curved tree branch, 4 cm thick and 1·63 m long.

A small area of the rose granite's surface was flattened with a dolerite hammer. The end of the tube, smeared with red water paint (probably red ochre in ancient times), made a circular mark by pressing it on the stone's surface, which was then grooved with a flint chisel driven by a dolerite hammer. This groove allowed the tube to be located for the initial grinding operation, achieved by continuously twisting the drill-shaft clockwise and anticlockwise on dry sand abrasive. At a depth of 5 mm, the bow could spin the located tube without it jumping out of the groove.

A team of three workers operated the drill (FIGURE 2), one worker at each end of the bow to drive it, the third worker holding the capstone. The bow-rope was sufficiently loosened to enable two complete turns to be made around the drill-shaft, which placed a bending stress upon the bow-shaft. This gave 50 cm of tight contact between the rope and the drill-shaft's circumference. Previous experimental tubular drilling indicated that a load of approximately 1kg/sq. cm needed to act on the drill-tube's end surface. The 8-cm diameter tube, with 1-mm thick walls, optimally required a total load of 2·5 kg. A greater load than this caused the drillers unnecessary work.

The workers' normal reciprocating strokes, each approximately 50 cm in length, turned the drill-shaft at a rate of 120 revolutions per

	hole depth	**time taken (hours)**	**tube length lost**	**volume (cu.cm) of lost copper**	**weight (gm) of lost copper**	**volume (cu. cm) of drilled stone**	**weight (gm) of drilled stone**	**cutting rate (cu cm/ hour)**	**revs/ minute**	**ratio 1**	**ratio 2**	**ratio 3**
dry sand	6 cm	20	9 cm	22·4	200	104	280	5·2	120	1:4·6	1:1·4	1:0·66

TABLE 2. *The data obtained from the tubular drilling of rose granite with a copper tube in use with dry sand abrasive.*

minute. The driller pushing the bow simultaneously assisted the other driller pulling it; these actions automatically reversed at the end of each stroke. Resisting the reciprocating strokes was not too difficult for the worker holding the capstone, although keeping it completely still was impossible. Some dry sand, trickled around the drill-tube, found its way down to the cutting face. Later measurements showed that about 250 g were used by the saw, and the drill, to grind away 1 cu. cm of the granite. Water in the sand abrasive made the drill-tube more difficult to turn and washed away the copper particles. Dry sand powder is easy to remove; it sticks together inside the drill-tube and can periodically be withdrawn from the hole (Stocks 1986a: 27).

The gyratory actions of the drill-tube's exterior wall wore the hole into a taper which sloped inward to its bottom, and the tube's interior wall wore the core into a taper, which was narrower at the top and wider at the bottom. The tubular slot, importantly, also became tapered. Additionally, the drill-tube's lateral movements across the slot, caused by the bow's reciprocating action, overcut it; this phenomenon reduced as the hole deepened. The drilling results are summarized in TABLE 2. The three ratios expressing the volume, weight and length of the copper abraded off the drill-tube to the volume, weight and depth of the drilled granite are recorded as 1, 2 and 3 respectively.

The core was removed from the drilled granite by soundly hammering two adjacently placed tapered chisels vertically into the tapered slot: the slot and the chisels' tapers fitted almost perfectly. The chisels acted on a short arc of the top of the core's circumference, using its length as a lever. This forced the core over, causing the brittle granite immediately beneath the chisels to be placed under such tension that it parted completely, allowing the core to be extracted in a single piece (FIGURE 3). Horizontal striations, similar to ancient ones in rose granite (e.g. the four tapered lifting holes in the lid of Prince Akhet-Hotep's granite sarcophagus, Brooklyn Museum 48.110), were visible both in the wall of the hole, and upon the core.

The granite cutting experiment

The process of preparing an area of 400 sq. cm of a granite block with a dolerite hammer and a flat quartzite rubber acting on dry sand, for the cutting of a hieroglyph, took a worker four hours to complete. After marking the biliteral sign, *nb*, 15 cm long, 3 cm at its widest point, upon the flattened surface with chalk, stone hammer-driven flint chisels were used to cut into the feldspar crystals. This action isolated the adjacent quartz and mica crystals, which were hacked away with further blows of the tools. Flint punches refined the surface left by the chisels. The chisels and punches suffered considerable damage during use, requiring frequent knapping to restore their edges and points.

The sign was cut out to a depth of 4 mm, its volume of 12 cu. cm being removed in 2 hours 30 minutes, the rate of cutting being approximately 5 cu. cm/hour. Chisels and punches were also made from chert nodules obtained from the Luxor region. These tools were unable to make any significant impression on the feldspar crystals: the hardness of chert *critically* falls below that of flint.

Discussion

The experimental sawing of the rose granite with the wet and dry sand abrasive indicates that the stone was cut more favourably with the dry sand. There is no requirement for a stone-cutting saw to be notched; copper removed to notch the saw is wasted, and reduces the area of the cutting edge. The wooden frame is unnecessary for such a rigid blade, and in a tall block of stone would eventually limit the depth to which a saw can cut. However, stone weights at either end allow a saw to cut through the stone without restriction.

The drawbacks with wet sand are an increase in the effort to move the saw, the provision of the water and the consequential loss of the copper particles from the waste powders. On the other hand, dry sand can be used in locations far from water, an important consideration in Egypt. The grey-coloured copper-contaminated waste powders from the sawing and drilling of granite have been made into experimental blue glazes (Stocks 1989: 21–6; 1997: 179–82), and it is possible that ancient craftworkers regularly used this resource to make some of their faience glazes.

For dry sand, the ratios of the average weights of the copper worn from the Aswan tools to the average weights of the sawn and drilled granite are similar to the ratios obtained from my earlier Manchester sawing and drilling experiments (Stocks 1986a: 24–9; 1988: I, 100–143). I feel that fully experienced ancient teams could have sawn and drilled the granite at approximately twice the rates achieved by the modern teams (Stocks 1999: table 1). The Aswan drill-tube and wooden shaft, bow-shaft and capstone needed no adjustment or repair during the drilling period. Only the bow-rope needed occasional tightening; the rope lasted 18 drilling hours before becoming badly frayed, when it was replaced.

The use of chert chisels and punches upon the rose granite clearly indicated that they were unable to cut this particular stone. However, the flint tools were capable of cutting into the feldspar crystals, allowing the harder quartz to be attacked and removed from the stone's matrix.

The abundance of quartz sand, flint nodules, and the availability of copper for making saws and tubes, allowed ancient Egyptian craftworkers to achieve three of the most formidable stone-working operations: namely, the sawing, drilling and cutting of the rose granite.

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In situ preservation as a dynamic process: the example of Sutton Common, UK

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In situ *preservation is a complex and dynamic process, which requires an understanding of the nature and scale of the material to be preserved, an understanding of the context of the site in terms of managerial needs and a programme of scientific monitoring of changes within the burial environment. The example of a rural archaeological landscape in northeast England, which is undergoing a programme of hydrological management, is considered.*

Key-words: In situ preservation, wetland archaeology, palaeoenvironment, monitoring, Sutton Common

Introduction

The need for long-term in-ground protection of the archaeological resource, or *in situ* preservation, is a stated objective of national and international agencies concerned with the future of the archaeological resource. This is asserted in English Planning Policy Guidance 16, 'Archaeology and Planning' (Department of the

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26

Roman Stoneworking Methods in the Eastern Desert of Egypt

Denys Stocks

Like the Egyptians before them, the Romans were fascinated with ornamental objects manufactured from attractive stones, some of which they extracted from the quarries located in the Eastern Desert of Egypt during the first four centuries AD. In particular, the quarries situated at Gebel Dokhan (Mons Porphyrites), close to the latitude of Asyut, but considerably nearer to the Red Sea than the Nile valley, supplied black and purple porphyry (hardness Mohs 7). About 50km to the south, workers extracted the grey granite (Mohs 7) from the quarries located at Mons Claudianus.

The purple porphyry, more usually known as imperial porphyry, is a fine-grained igneous stone containing relatively larger crystals of feldspar. It was used for architectural components, statuary, baths and sarcophagi. The columns and blocks from the quarries at Mons Porphyrites and Mons Claudianus were transported along roads to the Nile at Qena (Murray 1925: 138-141, plate XI) for the onward journey by river and sea. The porphyry has been found in Britain, Constantinople and Baalbek, but chiefly in Rome. The slightly foliated, igneous grey granite (Meredith 1952: 101) has also been identified in Rome, and in the ruins of Diocletian's palace in Spalato (Split).

Tool marks found on the porphyry and granite

David Meredith (1952: 98-101) refers to the quarries and associated areas around Mons Porphyrites. There, the Roman workers used a late ancient Egyptian method, evidenced by a line of deeply cut, oblong-shaped slots, for splitting the porphyry from the quarry face. It is likely that stone, or wrought iron, wedges were forcibly driven into every slot until a fissure opened up, linking the slots together. In elevated places, to catch the wind, were situated small, burnt-brick furnaces, indicating the heating of wrought iron and/or steel tools for re-forging and hardening, achieved by quenching the hot metal in water contained in the nearby hollowed-out stone troughs. Halfway through a stone block in a small quarry off the Wadi Ghazza (Meredith 1952: 100), its position probably associated with the quarrying operations at Mons Claudianus, was a saw-cut, but no definite evidence for the block's date. The approximate thickness of the saw's blade could be inferred from the width of the cut at the point where the block split.

Many of the columns and blocks were extremely heavy. Even after shaping in the quarries and at places along the transportation routes, one column weighed over 200 tonnes (Meredith 1952: 94). For example, chippings of Claudianus stone were found at a small station along an exit route from the Mons Claudianus quarries (Meredith and Tregenza 1949: 125-126). It made sense to remove as much stone as possible from large objects before transportation from a quarry, a measure practised by the ancient Egyptians during Dynastic times (Peck 1999: 655). Meredith (1952: 100) mentions evidence for the shaping of baths and sarcophagi in masons' huts near to the loading ramps, and at a point on the road connecting Mons Claudianus to the Nile valley.

The stonemasons at Gebel Dokhan used tools to chip or stipple stone blocks to an approximate shape, working the stone in regular, roughly parallel grooves or striations (Meredith 1952: 100). Also, some faces of the blocks were smoothed prior to the cutting of the inscriptions. What tool-making materials, and tool types, did the Roman masons employ for working the porphyry and granite in the Eastern Desert? Were steel (see below), an alloy of iron and carbon, tools capable of performing *all* of the stonecutting operations – the rough and the smooth surface shaping, the cutting of the inscriptions and the sawing - or were they only used for certain jobs? Were other tool materials being employed for the more exacting tasks, such as the engraving of inscriptions? Did Roman craftworkers assimilate and employ any long-standing ancient Egyptian methods and tools for working the porphyry and granite into artefacts?

Some experimental testing of a steel chisel and a steel punch on igneous stones

The classical writer, Theophrastus (fourth to the third century BC), provides a valuable insight as to whether iron or stone tools were used for cutting stones of different hardnesses. In Books LXXII and LXXV, of *History of Stones* (Hill 1774: 177, 181), Theophrastus says, 'As that some of the Stones before named are of so firm a Texture, that they are not subject to Injuries, and are not to be cut by Instruments of Iron, but only by other stones…and others yet, which may be cut with Iron, but the Instruments must be dull and blunt: which is much as if they were not cut by Iron.'

Early in the last century, Engelbach (1923: 40) confirmed Theophrastus's statement by trying to cut the granite with an iron chisel, but became convinced that the ancient Egyptians used a much harder tool upon this stone. The iron tools available in Theophrastus's time were probably inferior in hardness and toughness than the steel tools (Tylecote 1962: 244, table 80) likely to have been available to the Roman masons in the Eastern Desert. This is suggested by the hardness tests conducted on a second century AD Roman high carbon steel stonemason's chisel from Chesterholm, UK, which revealed a variable edge hardness of 579 to 464 DPN (Diamond Pyramid Number), with the body of the chisel at 136 DPN (Pearson & Smythe

1938: 141-145). The carbon content of the edge was variable, thus accounting for the fluctuating hardness result.

The constituents of the edge of this chisel - work-hardened ferrite and some martensite and other materials - prove an intention to harden the tool by heating and quenching. However, more importantly, the smith deliberately increased the carbon content, albeit unequally, by placing the semi-forged tool into a reducing area of the hearth (Tylecote 1962: 244-245, fig. 63). I am going to assume, for this study, that the Roman masons in the Eastern Desert were supplied with steel tools capable of being forged and hardened to at least the hardness of the second century AD Chesterholm chisel.

The Chesterholm chisel's maximum hardness of 579 DPN is considerably lower than the hardness of a modern steel chisel (800 DPN), but much harder than the hardest copper, leaded bronze and bronze chisels (140, 201 and 247 DPN respectively) that I made and tested on sedimentary, metamorphic and igneous stones (Stocks 1982: 79-94; 1988: I, 64-99; II, 314-318, 328-329). These tests proved that igneous stones cannot possibly be cut with copper, or copper alloy, chisels or punches (Stocks 1982: 81; 1988: I, 87-88). Experiments with the modern steel chisel, made from a high carbon chisel steel (more than 0.60% carbon), upon the flattened and smoothed surface of the igneous stone, grano-diorite (Mohs 7), caused the tool to suffer immediate severe damage to its cutting edge (Stocks 1982: 81; 1986a: 26; 1988: I, 87-88). Modern lettering in igneous stones is achieved with tungsten carbide tipped chisels, an even harder and tougher material than hammered and hardened chisel steel.

My experiments with the steel chisel indicated that while modern, and therefore Roman, steel chisels could not cut into a flat and smoothed igneous stone surface, modern hardened steel *punches* can chip the rough stone surfaces left after separating a block from the quarry face. This method is in use today in Hamada Rashwan's rose granite quarry situated in eastern Aswan, Upper Egypt. Here, a mason creates sculptures by chipping away the coarse-grained granite with a hardened steel punch (probably 800 DPN, but not tested for hardness). The original point gradually becomes flattened as the chipping proceeds, making a small square at the end of the four-sided taper. This square forms edges at the four sides of the taper, each possessing an angle of approximately 95°. These can be made to act as chisel-edges, as well as using the tool as a straightforward punch. A flat-tapered chisel's edge forms an angle of approximately 60°, which is likely to become blunted more quickly than a punch's four obtuse edges. Modern steel flat-ended punches are quite effective on rough igneous stone surfaces for a time, but still need fairly frequent re-forging and hardening.

I tested a hardened steel punch (800 DPN) by driving it into the flattened and smoothed grano-diorite surface. The four obtuse chisel-edges were rapidly blunted, metal being torn from them. The punch caused some limited damage to the stone, but the necessarily frequent re-forging and hardening of the tool was counter-productive to its efficient use. The Aswan quarry smith quenched the last few millimetres of a re-forged point by placing the tool vertically in shallow cold water contained in a metal tray. I observed him busily hammering and hardening dozens of punches at a time. However, the total number of punches in circulation was sufficiently high to keep all of the masons working without interruption. Did the Romans practise this method in the Eastern Desert?

Although a Roman flat-tapered steel *chisel* of 579 DPN might have been capable of chipping away small pieces of the fine-grained porphyry from a block's rough surface, a slightly easier stone to cut than the Aswan rose granite, its edge would rapidly have become blunted. This would have necessitated unacceptably frequent re-forging and hardening. My tests with the modern steel punch on the grano-diorite suggest that the type of Roman tool in use for roughly shaping the porphyry and granite in the Eastern Desert was probably a punch.

The above experimental evidence suggests that Theophrastus accurately referred to the inability of Egyptian fourth/third century BC iron tools to cut igneous stones, and the poor ability of those tools effectively to cut stones somewhat softer than igneous stones. Iron tools were not substantially in use in Egypt until the Twenty-sixth Dynasty. Therefore, before, and even after, this period the ancient Egyptian stone-worker needed to use a variety of indigenous stones, locally available in abundant quantities, for shaping the hard stones, in addition to cutting the hieroglyphs and reliefs into prepared igneous stone surfaces.

Extensive tests of dolerite, silicified, or crystalline, limestone, flint and chert chisels and punches (Stocks 1982: 164-197; 1988: II, 246-273) showed that only flint (Mohs 7) tools can truly cut into *all* Egyptian igneous stones, particularly the coarse-grained granite. Chert, which is similar in appearance to flint, is critically softer than it (Stocks 2001: 93). Dolerite, chert and silicified limestone mauls and hammers are attested in Egypt for pounding or bruising igneous stone surfaces smooth (Petrie 1938: 30). The test use of the flint chisels and punches upon igneous stones left marks not unlike those seen on unfinished Egyptian inscriptions in hard stone (e.g. a rose granite column, British Museum EA1123). Did the Roman masons cut the inscriptions, and the wedge slots, into the porphyry and granite at Gebel Dokhan and Mons Claudianus with flint chisels and punches, saving unnecessary serious damage to their steel tools?

Roman quarry workers and masons certainly had relatively easy access to grey flint at the Wadi Abu Had, some 50km to the north of Gebel Dokhan, and there is evidence for a fourth century AD Roman installation there (Bomann

1999: 861, 863). This installation (WAH 30) is contemporary with the late Roman extraction of porphyry at Mons Porphyrites, but there may be earlier, as yet unknown, Roman association with the Wadi Abu Had during the first to the third centuries AD. Several small, late-Roman installations were also found by Bomann (1999: 861) in the Wadi Dib, which is adjacent to the Wadi Abu Had.

It is possible that the fourth-century AD Roman installation at Wadi Abu Had was connected with the collection of flint nodules contained in the limestone hills of Gebel Safr Abu Had, situated within the Wadi Abu Had (Bomann and Young 1994: 23-27, fig. 2). The nodules could have been knapped into chisels and punches near to the point of collection, reducing weight to a minimum for transportation, or taken back to Gebel Dokhan and Mons Claudianus for knapping there. The *knapping* of flint nodules into tools creates a considerable number of noticeable flakes, but it is unlikely that the small fragments broken from any flint chisels and punches used for *cutting* the inscriptions into the porphyry and granite blocks would immediately be visible in the heavily-sanded quarry sites today.

Test cutting of an igneous stone with a steel saw and sand abrasive

Pliny the Elder's (first century AD) Book XXXVI, 9, *Natural History* (Eichholz 1962: 41) gives an account of the technical aspects of sawing marble. Pliny says:
'The cutting of marble is effected apparently by iron, but actually by sand, for the saw merely presses the sand upon a very thinly traced line, and then the passage of the instrument, owing to the rapid movement to and fro, is in itself enough to cut the stone.'

Marble's hardness is Mohs 4-5, so not as hard as porphyry and granite. However, archaeological evidence and tests have shown that ancient Egyptian craftworkers *necessarily* sawed stones above the hardness of Mohs 3 by the use of a flat-edged copper saw using sand as an abrasive (Goneim 1956: 108; Stocks 1982: 152; 1999: 919). In ancient Egypt, it is likely that bronze superseded copper as a saw material from the Middle Kingdom onward. However, the use of iron as a material for stonecutting saws with sand abrasive in the first century AD, not necessarily in Egypt, is confirmed by Pliny's remarks. Nevertheless, it is, in the light of the evidence for a stonecutting saw near to Mons Claudianus, reasonable to suggest that the first to the fourth century AD Roman stoneworkers employed saws of wrought iron in the Eastern Desert of Egypt.

Preliminary small-scale experiments to make and test copper, bronze and mild steel flat-edged saws with dry sand abrasive on various sedimentary, metamorphic and igneous stones were carried out in Manchester during the early 1980s (Stocks 1982: 153-157; 1988: I, 140-143, II, 340, 343). All of the saw materials effectively cut igneous stones. The experimental sawing of a fine-grained granite with the low carbon content (less than 0.30% carbon) annealed mild steel saw (131 DPN), similar to annealed wrought iron's characteristics, indicated that Roman iron saws could effectively have cut through the imperial porphyry and grey granite. The steel saw's rate of cutting was lower than the annealed copper and bronze (42 and 75 DPN respectively) saws' cutting rates.

In all of the three saw materials it was found that dry, rather than wet or drying-out, sand acted as a fluid under the pressure and reciprocating movement of the saws, causing a rapid interchange of fresh, unused quartz crystals at the saws' flat cutting edges. With any saw blade, the angular crystals embedded into the flat edge and striated the stone under the blade and along the saw-slot's walls, sometimes causing new striations, at other times reinstating old ones, as the blade moved backwards and forwards along the stone. The tests suggested that an iron saw needed to be as soft as possible, allowing the angular quartz crystals to embed themselves more easily into the metal, thus increasing its efficiency as a cutting tool.

Based upon the experimental steel saw cutting rate of 3cm³/hour for granite, and the experience gained from my large-scale sawing tests in Hamada Rashwan's granite quarry during March 1999 (Stocks 2001: 90-91, figs.1,2), the estimated Roman rate for sawing the porphyry and granite with a long wrought iron saw driven by two workers is approximately 18cm³/hour for both stones. The ratio of the weight of the metal worn off the experimental saw to the weight of the sawn granite was 1: 2.

Discussion

The tests with a modern flat-tapered steel chisel (800 DPN) indicated its inability to cut *into* a flattened igneous stone surface. The long cutting edge was immediately blunted, and pieces of the metal at the extreme ends of the edge were torn away. Softer (579 DPN), similarly shaped Roman steel chisels were likely to have suffered even greater damage upon the porphyry and granite in the Eastern Desert. Steel *punches* as hard as 579 DPN could have gradually chipped the stones into shape. However, punches of this hardness perform extremely poorly if used to cut wedge slots, or inscriptions, into a smoothed igneous surface. The harder test punch suffered considerable damage with little work performed upon the stone.

The presence of a fourth century AD Roman installation at the Wadi Abu Had provided the opportunity to collect flint nodules to make and supply flint chisels and punches to the masons at Gebel Dokhan and Mons Claudianus. Future examination of the quarries, and the Wadi Abu Had environs, may uncover evidence supporting this hypothesis for the fourth century AD, and earlier periods.

The experimental sawing of the fine-grained granite suggested a Roman cutting rate of 18cm³/hour for the Mons Claudianus granite and the Gebel Dokhan porphyry, with an acceptable rate of wear to a wrought iron saw.

Whether, after shaping, Roman masons hollowed out *all* of the baths and sarcophagi at, or near, the quarries to lessen their weight before transportation is uncertain. The long-established ancient Egyptian method for hollowing igneous stone sarcophagi involved the drilling of many adjacent holes with a bow-driven tube and sand abrasive, an efficient and safe technique (Petrie 1883: 84; Stocks 1999: 922; 2001: 91-93, figs.2,3). Copper, bronze and iron tubes are all capable of drilling igneous stones with sand abrasive (Stocks 1982: 95-151; 1986b: 29; 1988: I, 116-136; 2001: 91-93). Therefore, tubular drills of wrought iron may have been employed for the hollowing of Roman sarcophagi and baths in the quarries. However, like the Egyptian copper and bronze drill-tubes, no examples have ever been located. The finding of tapered stone cores, which were broken out of the tubular holes, indicates the tubular drilling of ancient Egyptian artefacts; such cores have been found at Giza. If indeed the Roman masons employed tubular drills in the quarries, the broken-out cores may still be buried in the sand in those areas where the drilling took place. This essay is offered as a tribute to Barri Jones, whose interest in ancient technology and enthusiasm for desert archaeology helped stimulate and maintain my own researches in Egypt.

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CHAPTER NINE

Technical and Material Interrelationships: Implications for Social Change in Ancient Egypt

Denys Stocks

9.1 Introduction

A series of experiments with replica and reconstructed ancient Egyptian tools have indicated the development of interrelated technology, tools and materials in key areas during the Predynastic period, significantly influencing the subsequent course of Egyptian civilization. In trying to understand the technical steps achieved by craftworkers, a study of the archaeological evidence preceded the manufacture and use of over 200 replica and reconstructed tools.

The establishment of tools and procedures for the manufacture of stone vessels contributed crucially to the growth of other technologies in the Naqada II and III periods; the rapid expansion of hard stone vessel production in Naqada II indicates the introduction of reliable vessel manufacturing methods. What were these new production techniques and why did they emerge and affect later industrial developments? In endeavouring to answer these questions, the manufacture of hard and soft stone vessels was used as a focal point in investigating Predynastic and Dynastic technical changes.

9.2 Shaping Stone, Wood and Metal

The introduction of smelted and cast copper at the commencement of the Gerzean culture enabled craftworkers to imitate the shapes of certain stone tools in copper. I propose that the flint (hardness Mohs 7) end-scraper, the serrated flint sickle and knife, the straight-edged flint knife and the flint hand-axe were transformed into five copper tools, namely, the chisel, the adze, the saw, the knife and the axe. The long, slim flint end-scraper, held in both hands, can be used to pare materials in a direction *away* from the worker. However, by binding a flint end-scraper, or a similarly designed copper tool, to a long wooden shaft, now called an adze, it could be swung *towards* the operator for shaving thin pieces from wood and soft limestone, and by holding the tool in one hand it could be struck, as a chisel, by a mallet. The Predynastic copper adze-blade and the flat-tapered chisel are similar in design and probably modelled on the flint end-scraper.

Before the introduction of copper tools the Predynastic stoneworker was obliged solely to rely upon stone tools for shaping hard and soft stone artefacts. Certain stone objects can only ever be worked by stone tools, confirmed by the experimental test (Stocks 1988, I, 40-99, II, 314-18, 328-9, 334-9, 345-6, plate V, a, b) of twenty-five replica copper, leaded bronze and bronze chisels upon red sandstone, soft limestone (both Mohs 2.5), calcite (Mohs 4), hard limestone (Mohs 4-5), hard sandstone (Mohs 5), granite and diorite (both Mohs 7). The tests showed that all chisels were soon seriously damaged on all stones of hardness Mohs 4, and above. Copper and bronze chisels' edges were blunted, or torn away, to such an extent that constant sharpening, *even for cutting calcite*, caused unacceptable losses of metal from the tools. The experiments demonstrated that only gypsum (Mohs 2), steatite (Mohs 3), soft limestone, red sandstone, and all woods, could efficiently be carved and incised by copper, leaded bronze or bronze tools.

The experimental copper and bronze chisels and adze-blades were cast in open sand moulds and cold hammered with spherical stone mauls, just like ancient copper tools. Sand moulds can only be used once. However, at the Twelfth Dynasty workers' town of Kahun, in the Fayum, Flinders Petrie (1890, 29) found reusable, open pottery moulds for casting axe-heads, chisels and knives; pottery moulds allowed the mass production of identically shaped tools, increasing their availability for work. Petrie (1917, 61, plate LXXVII, W250) found an unworked copper knife, subsequently to be beaten thinner, cast to a thickness of 'about 1/4 inch' (6 mm). My experimental casting of a flat-edged, copper stone-cutting saw blade into a shallow, open sand mould revealed that the floor of the mould, when *just* completely covered by molten copper, created a 5 mm thick casting. This phenomenon is connected with saw slots up to '1/5 inch' (5 mm) wide, seen in hard stone artefacts by Petrie (1883, 174). These particular saws cut hard stone blocks, sarcophagi (in reality, giant stone vessels) and statuary to shape with quartz sand abrasive, and are closely related to the function of flat-ended copper tubular drills, employed for the initial hollowing of vessels' and sarcophagi interiors.

In the Eighteenth Dynasty tomb of Rekhmire, Thebes (Davies 1943, II, plate LXII), a scene shows bronze chisels in use for shaping soft limestone building blocks. Masons are depicted testing a block's surface flatness with two wooden rods, held upright and apart and tightly stretching a string between them. Each worker holds another upright rod against the string, determining how much excess stone needs removing at that particular point. Petrie (1890, 27, plate IX, 13) discovered the earliest known surface testing rods at Kahun. These three *matched* wooden rods were measured by Petrie and found to be equal in length 'within two or three thousandths of an inch' (0.05 mm). Three replica rods (Stocks 1987), adjusted to these tolerances by using a rudimentary calliper, proved that they can reveal surface inaccuracies as small as 0.25 mm along a length of 1.25 m, and therefore over a 1.25 metre square. These experiments indicate the employment of rods and string for testing the joining surfaces of casing blocks fitted into the Great Pyramid at Giza.

The serrated design, and use, of flint sickles and knives indicates a relationship to the design and use of copper saws. Test serrated flint knives cut wood efficiently. However, serrations on brittle flint tools suffer damage in use on hard, woody materials, whereas the tougher, thin copper saw, beaten from a cast copper plate, possessed an extended working life. Dynastic copper saws, with wooden handles, were used for cutting soft limestone and wood, and tests with replica saws demonstrated their efficiency upon soft limestone, red sandstone and all types of soft and hard woods.

Tomb representations (Davies 1943, II, plate LX) show stone statuary and other artefacts being bruised to shape by hand-held spherical stone mauls; granite was detached from its parent rock by pounding it with balls of dolerite (Mohs 7), until separating trenches surrounded a block or obelisk (Engelbach 1923, 42). Metalworkers also used spherical and hemispherical hand-held stone hammers for beating cast metal plates into thinner sheets on a stone anvil set on a wooden block, itself buried in the earth, and for shaping metal vessels placed upside down on a tripod anvil. Using an illustration in the tomb of Rekhmire as a guide (Davies 1943, II, plate LV), a reconstructed New Kingdom anvil consists of a forked branch, the forked end being placed on the ground at an acute angle. A long wooden rod passes easily through an upward slanting hole, drilled into the upper, single stem. The rod not only acts as the anvil's third leg, but also can be adjusted for work on both small and large vessels by sliding it through the hole.

Elongated, pointed stone picks, and edged axes, made of syenite, quartzite, silicified limestone (all Mohs 7), basalt and flint (Petrie 1917, 46, plate LIII, S74-86) dressed hard stone to a flat surface, where sawing was not employed, and for quarrying stones, such as limestone, sandstone and calcite. These tools were often supplied with handles (e.g. Metropolitan Museum of Art 20.3.190), but some stone picks and axes were gripped in two hands and directly swung against the stone (e.g. Metropolitan Museum of Art 09.183.5A-C). Replica stone picks, axes and mauls were adequate for roughly shaping hard stone, but for hieroglyphs and reliefs different tools and techniques were required.

Examination of finished and unfinished hard stone artefacts shows that *driven* chisels and punches were used for shaping them. Good examples of chisel marks can be seen on unfinished panels of incised hieroglyphs carved into a rose granite column in the Manchester Museum (1780). The unfinished hieroglyphs are crudely hacked out of the stone. Variations to the width and depth of the chisel marks indicate that several chisels were in use and that the strength of a hammer or mallet blow altered with each impact. Sometimes, directly adjacent to a chisel mark is a 'scar', where a small piece of the brittle stone has chipped away; punch marks can often be seen in the bottoms of hieroglyphs cut into hard stone artefacts. My experimental cutting of hieroglyphs in stone (Stocks 1988, II, 246-73, plates XXIV, b, XXV, b) indicates that only struck flint chisels and punches make such marks *after* a tool's cutting edge or point is positioned on an artefact's surface. Test flint chisels cut a test biliteral sign, *nb*, at the rate of 5.5 cm^3/hour into rose granite. (My assessment of the ancient cutting rate for granite is 15 cm^3/hour). The chisel marks resemble ancient unfinished hard stoneworking. Pointed punches abraded the stone to a smoother surface, now suitable for scraping by flints or grinding by stones. The surface was polished by a waste drilling product, consisting of finely ground sand/stone/copper powder, followed by mud applied by a leather lap. The same tools and techniques worked diorite, hard limestone, hard sandstone (Plate 9-1) and calcite.

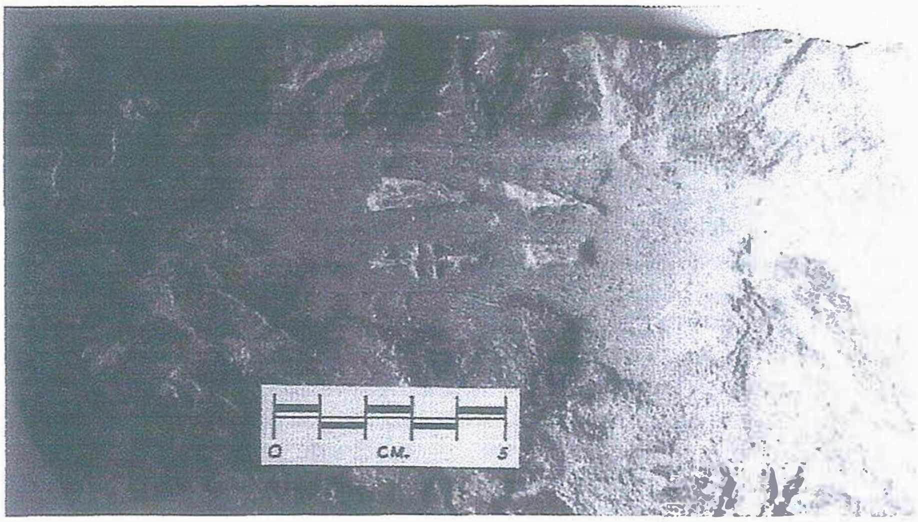

Plate 9-1 The ancient Egyptian word for flint (*ds*, 'sharp stone'), incised into hard sandstone by reconstructed flint chisels, punches and scrapers.

Petrie (1883, 173) examined incised lines ploughed through a Fourth Dynasty diorite bowl's surface, and tests showed that similar lines could be made with a flint graver. Other experiments demonstrated that forceful strokes with flint tools could cut copper and bronze with V-shaped incisions, comparable to some on four copper razors (British Museum 6079-82). Flints could initially scrape eyeholes in replica annealed (softened) copper and bronze needles; the scraped holes were pierced through by hammer-hardened copper and bronze punches, easily penetrating their own annealed metals. Although copper chisels were probably utilized to carve and incise soft limestone blocks, alongside flint chisels, flint scrapers were used to finish limestone relief hieroglyphs (Petrie 1938, 30). Scraping was employed to finish the bottoms and sides of hundreds of small incised hieroglyphs in a greywacke (Mohs 4-5) sarcophagus in the Musée du Louvre (N345 D9). However, a similar number of chipped hieroglyphs in an adjacent granite sarcophagus (N346 D10) were not scraped, a prolonged task. The present tests (Stocks 1988, II, 264, 298) show that flint tools do scrape igneous stone, but are more effective for greywacke, calcite, serpentine (Mohs 4), hard and soft limestone, hard and soft sandstone, gypsum, steatite and all woods.

The experimental flint chisels and punches performed well on hard stone, but soon suffered damage to their cutting edges and points. However, knapping a flint chisel creates a new edge, reducing the tool's size over a period of time; these tools are expendable. It is likely that a substantial flint-knapping industry existed to supply craftworkers with new tools for working hard stone at building sites, suggested by the finding of large amounts of flint flakes near to the pyramids of Cheops and Senwosret I by Petrie (1883, 213) and Dieter Arnold (1991, 48) respectively.

9.3 Drilling and Boring Stone and Wood

My stone drilling and boring tests (Stocks 1986a; 1988, I, 100-143, 168-213) revealed a significantly different picture to the manner in which stone and metal tools cut both soft and hard stones. Before *ca.* 3500 BC, craftworkers necessarily hollowed hard stone vessels by employing grinding techniques, the only non-destructive method available to them. Contrary to a flint chisel's ability to shape hard stones, tests show that flint crescents cannot penetrate them. These tests demonstrated that flint crescents only satisfactorily bore gypsum, soft limestone and steatite, *but not calcite*: a flint crescent's cutting edges splinter, when rotated against calcite, just as they do against harder stones.

A difficulty with hollowing Badarian and Naqada I hard stone vessels was that *all* the stone had to be ground away. Craftworkers were obliged to continue using this method until the establishment of copper casting, when the expansion of hard stone vessel production indicates that the copper tubular drill was introduced. The predecessor, and pattern, for the copper drill-tube was probably the common reed, *Phragmites communis*. Predynastic and Dynastic furnaceworkers and jewellers employed the reed as a blowpipe, crucially adapting it into a tube by jabbing a stick through the leaf-joints and uniting the previously separate hollow sections. My blowpipe and furnace experiments (Stocks 1993a, 64-6) established that four to six ancient workers supplied enough air to melt up to 1.3 kg of copper in a single crucible, a maximum capacity determined by Christopher Davey (1985, 142-8). Probably, early stone vessel workers realized that a reed tube ground out a tubular-shaped slot: this technology allows the removal of a relatively small amount of stone by drilling, but achieves a full-sized hole after snapping off the core.

Petrie (1883, 174-5) measured Fourth Dynasty tubular drill-holes and saw slots in basalt, granite and syenite. He found that tubular drills varied from '1/4 inch' (6 mm) to '5 inches' (127 mm) in diameter, and that the walls varied from '1/30 inch' (0.8 mm) to '1/5 inch' (5 mm) in thickness. Saw slot widths also varied from '1/30' to '1/5' inch. Possibly, smaller copper tubes were made by rolling beaten sheet around a wooden former, and larger tubes by casting the metal into tubular-shaped moulds in sand. An experimental copper tube, 70 mm outside diameter, wall thickness 5 mm, was satisfactorily cast in a mould, and a flat-edged saw cast to a thickness of 5 mm. My calculations indicate that a single, large diameter copper tube, or a long stone-cutting saw, required sufficient metal to need the concurrent pouring of several crucibles and, therefore, the functioning of multiple numbers of furnaces at a single location from Old Kingdom times.

Egyptian workers possessed five bow-driven tools: a waisted fire stick; a waisted wooden drill-stock that drove interchangeable tools, such as a short fire stick and a metal auger; copper, and later bronze, tubular drills; single bead drills; a set of bronze drill-rods and long handles, no examples discovered, for simultaneously perforating up to five stone beads together, and illustrated in six New Kingdom tombs at Thebes, Upper Egypt. A shaft was usually waisted, enabling a stretched bow-string to engage on a wider diameter, automatically increasing its grip. A replica drillstock, fitted with a copper auger, drilled softwoods at the rate of 66 cm^3/hour, hardwoods at the average rate of 25 cm^3/hour.

The New Kingdom multiple bead drilling equipment, illustrated in the tomb of Sebekhotep (Figure 9-2), enabled rows of drillers to mass-produce perforations in stone beads. These were probably set at intervals into a dried mud block occupying a hollow tabletop, an idea, perhaps, borrowed from the wooden mud brick mould. The reconstructed apparatus, using watery paste made from the finely ground waste sand / stone / copper powder, revealed that a 10 mm diameter calcite bead could be drilled by a 2 mm diameter bronze drill-rod in one hour. A 10 mm diameter amethyst (Mohs 7) bead could be drilled by a 1 mm diameter drill in four to five hours. The New Kingdom mass production tool, using three drills, reduced perforation times to a third of the single rate, thereby lowering the cost of stone beads for jewellery manufacture, and increasing their availability (Stocks 1989).

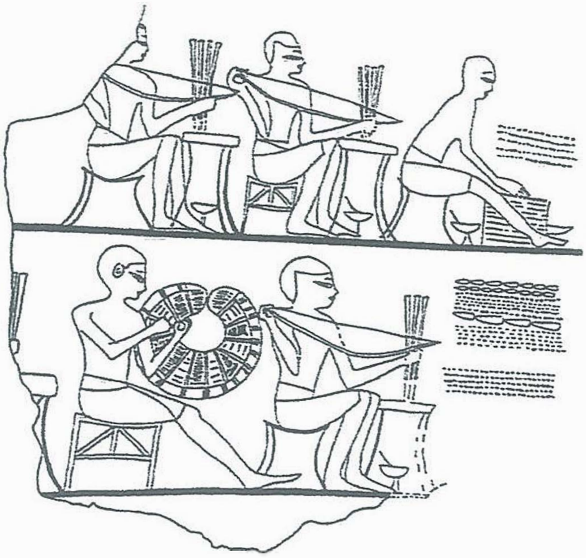

Figure 9-2. Three stone bead drillers illustrated in the Eighteenth Dynasty tomb of Sebekhotep, Thebes. Each craftworker uses the multiple bead-drilling tool. (After British Museum exhibit 920).

A Late Gerzean syenite vessel (Manchester Museum 1776) has both its lugs perforated by a single hole, drilled from either side so as to meet in the middle; each side of the hole tapers from a maximum diameter at the surface to a minimum diameter at the lug's centre. This phenomenon is positive evidence for a tube wobbling around the point where a bow-string rotates it. A relatively short copper tube, necessarily copper for syenite, was force-fitted to the lower part of a longer wooden shaft, its upper end rotating in a lubricated hemispherical stone bearing. Striations horizontal to the holes' vertical axes travel around the interior walls.

When magnified, these striations are rough and uneven, about 0.25 mm deep and wide, but not always regular and parallel. Tapered cores were similarly striated. Comparable straight, parallel striations are seen in sawn hard stone artefacts (e.g. a Fourth Dynasty basalt triad of Mycerinus, Cairo Museum JE46499).

Alfred Lucas (1962, 74) and Andrew Reisner (1931, 180) both found a light green powder, consisting of very fine grains of quartz sand, in the bottoms of tubular holes in Third and Fourth Dynasty stone artefacts. The colour was due to a copper compound, evidently from copper tubular drills. Petrie (1883, 174) also reported sand grains and green staining in Fourth Dynasty saw cuts made in basalt blocks. In a tubular hole drilled into an Eighteenth Dynasty granite doorpost (Metropolitan Museum of Art 13.183.2) are minute particles of bronze, evidence that this material was now employed for tubes. J.E. Quibell and F.W. Green (1902, II, 17) found a quantity of sand that had been used as an abrading material in an Old Kingdom vase grinder's workshop.

The copper tubular drilling experiments determined that *wet* sand abrasive is not efficient. The essence of drilling and boring with sand, containing quartz crystals (Mohs 7), is the continual replacement of worn crystals by fresh, angular ones at the cutting face. Wet sand, or wet sand drying-out, prevents this, whereas dry sand acts like a fluid under pressure and motion. Very wet, or fluid, sand will interchange, but is unsuitable for other reasons.

Dry ground sand turns into a dense fine powder, similar to the texture of flour. Hard limestone and calcite derived powders are almost white; harder stone derived powders, e.g. granite and basalt, are dark grey or nearly black in colour. These powders *appear and feel* like powdered emery. Most of the powder packs inside a tube and sticks together in one mass when it is removed from a hole. In this way, the powder from dry sand can be withdrawn from deep, tubular holes drilled into sarcophagi, whereas fluid powder cannot. Suspended in the powder are unworn crystals that create striations in the core and hole wall due to the gyratory actions of a bow-driven tube. These striations are worn away at times but are reinstated, changing their direction and depth as the drilling proceeds. Linear striations occurred in test slots made by the reconstructed flat-edged saw. Sand crystals, gradually wearing the tools away and contaminating the sand with copper particles, similarly striated this saw, and the tubes.

The drilling tests with bow-driven reed tubes indicate that *dry* sand must be used, as the woody stem collapses in use with wet sand. Reed tubes can only drill calcite, soft and hard limestone, marble (Mohs 4-5), red sandstone, serpentine and steatite. The test bow-driven reed tube drilling rates for soft limestone, hard limestone and calcite are 12, 8 and 8 cm^3/hour respectively. Bow-driven copper tube drilling rates for granite, diorite, calcite and hard limestone are 2, 2, 30 and 30 cm^3/hour respectively. The drilling and sawing tests on granite, hard limestone and calcite determined that the ratio of the *weight* of copper worn off the tools to the *weight* of drilled or sawn stone is 1:0.9, 1:8 and 1:12 respectively. The average consumption of sand and the times for drilling or sawing 1 cm^3 of these stones are 250, 50 and 45g and 40, 5 and 2 minutes. These data permit the calculation of the approximate quantities of copper and sand consumed, and the manufacturing time, for Cheops' granite sarcophagus. Using Petrie's (1883, 84) measurements of a drill-tube mark, calculations show that it was caused by a copper tube six royal fingers (110 mm) in diameter. This diameter drill-tube fits exactly 18 and six times along the internal length and width respectively. The sawing, drilling and finishing procedures used about 430 kg of copper and 37 tonnes of sand during a period of approximately 21 months.

The powders derived from drilling calcite and hard limestone were each mixed with water and sodium bicarbonate to form a stiff paste that became a whitish, friable core material after firing at 850°C. The granite derived powders were mixed with sodium bicarbonate and water and fired at 950°C, turning the material into a blue, vitreous glaze. The experimental cores and glazes are similar to ancient faience (Stocks 1997). Possibly, Predynastic craftworkers replaced carved steatite cores with moulded or modelled waste calcite or hard limestone derived powders, and malachite as a colourant for blue and green faience glazes by using waste copper-contaminated igneous stone derived powders.

The combined stone vessel drilling and boring tool is illustrated in a number of Dynastic tombs, although the examined techniques for drilling and boring vessels suggest that it was introduced in the Early Gerzean period. In an unfinished, uncatalogued stone vase (Petrie Collection, University College London), the parallel-sided core remains in its parallel-sided hole, clear evidence for a tubular drill carefully twisted and reverse twisted around its longitudinal axis. The Old Kingdom tool, probably manufactured from a forked tree branch, consisted of a straight shaft, with one of the stems cut away, the other remaining at an obtuse angle to form a handle: this method was also employed to make bow-shafts. Stone weights put pressure on a drill-tube or stone borer. For drilling, a copper tube was force-fitted to the shaft's bottom end. After core removal, lashing an inverted forked branch to the main shaft hollowed bulbous vessels by driving increasingly longer figure-of-eight shaped stone borers. Striations 0.25 mm wide and deep on the undersides of borers indicate that sand abrasive was in use with them. An inverted truncated cone borer, possessing two opposite slots for the fork, shaped a vessel's internal neck; the fork also drove flint crescentic borers. Wide-mouthed vessels were drilled with adjacent holes to weaken the central mass (e.g. Cairo Museum JE18758). Petrie (1917, plate LII, 61) found a tubular core of basalt, indicating that two different diameter tubes were used on the same axis to weaken a large core.

The experiments with reconstructed equipment (Stocks 1986b, 1993b) showed that the tool was continuously twisted by wrist action, clockwise by about 90° and anticlockwise to its starting position. This allowed tubes to cut around the whole circumference, but in using a figure-of-eight borer a worker periodically changed the grip on the tool at the end of a full twist. The tool drilled an experimental 107 mm high limestone vase in five hours and took 10 hours to bore its internal configuration, after four hours of shaping and polishing. Twist/reverse twist-driven copper tube drilling rates for granite, diorite, calcite and hard limestone are 0.4, 0.4, 6 and 6 cm^3/hour respectively, indicating that this type of drilling is *five* times slower than bow-drilling a similar stone.

9.4 Implications for Social and Organizational Changes

All the technical evidence described indicates the establishment of an interrelated industrial society that became sufficiently developed in the Predynastic period to supply significant numbers of valuable artefacts, particularly stone vessels, for domestic use and foreign trade. The experimental drilling and sawing of stone suggests that large amounts of copper ore were mined and processed *just* to replace the thousands of tonnes of copper lost from tubular drills and saws over millennia, particularly for making hard stone sarcophagi. This implies that an organization was developed to administer and implement the following pivotal industrial procedures: the mining and smelting of copper ores; the transportation of copper ingots to work centres; the casting and beating of copper into saws and tubes; the sawing and drilling of artefacts; the probable collection and supply of waste powders to stone polishers, bead drillers and faience manufacturers.

Several important inventive steps progressively increased the production of artefacts, making them accessible to wider groups of people: this slowly altered the structure of Egyptian society. The most notable advances were the transformation of specific flint tools into copper; the conversion of the reed tube into a blowpipe and a drill-tube, later copied in copper and driven by the bow and the Twist/Reverse Twist Drill (TRTD); stone-cutting saws; reusable pottery moulds; the interchangeable tool drillstock; surface testing rods; expendable flint tools; the adaptation of tree branches to make bows, tripod anvils and TRTD main shafts and their associated forked shafts for borers; the New Kingdom multiple bead drilling apparatus.

The gradual development of interdependent processes must have employed ever-increasing numbers of workers, and consumed huge amounts of materials. This implies vigorous organizational abilities to meet each new technical demand. In particular, the gathering and transportation of desert sand and flint potstones, and their associated manufacturing processes of sawing, drilling, boring, knapping and stone-cutting, became a major industrial enterprise.

It is clear that Egyptian rulers, and increasingly their subordinates, progressively ordered more complicated and elegant artefacts *partly* because existing technology could be adapted by craftworkers. This in turn drove an economy geared to the production of wealth, enabling privileges to flow to the few from its creation.

DISCUSSION

R (Hansen) Two remarks. Recently, Mark Lehner found an Old Kingdom copper workshop in Giza. Secondly, in the New Kingdom period in Deir el-Medina, the loss of copper was recorded. In the texts mention is made of the weighing of tools in order to determine the wear.

R (Haikal) In the Sinai, an area where expeditions were sent to obtain copper, moulds have been found for the production of copper tools.

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2003b. ‘Immutable laws of friction: preparing and fitting stone blocks into the Great Pyramid of Giza’, *Antiquity* 77: 572-8.

Immutable laws of friction: preparing and fitting stone blocks into the Great Pyramid of Giza

Denys A. Stocks[1]

How did the pyramid builders prepare and fit large stone blocks so that they were horizontal, orthogonal and flattened to within one hundredth of an inch? The author's experiments suggest that the surfaces were prepared using basic instruments made of rods and string, while to move the blocks the immutable laws of friction were mitigated by lubricating with mud and gypsum.

Keywords: Egypt, pyramids, construction, ramps, rods and string.

Introduction

The exact techniques employed by ancient Egyptian craftworkers in the construction of the Great Pyramid of Khufu at Giza during the Fourth Dynasty (*c.* 2649-2513 BC) are still uncertain. Two of the major problems concern the preparation and fitting of the large stone blocks, which were achieved to a high degree of accuracy. A key factor was the friction developed between two surfaces, which controlled the degree of sliding of one stone block over another. Here, data obtained from experiments in measuring the blocks shows how plane surfaces could be prepared which were nearly perfectly flat. Other experiments showed how the blocks could be moved, with the use of lubrication, to lessen the effects of the immutable laws of friction.

Preparing surfaces

The tasks of the mason consist of producing horizontal and vertical surfaces which are precisely flat, and these would require cutting and shaping tools and measuring instruments. Replicated and reconstructed copper, bronze and stone tools for shaping hard and soft stones have been manufactured and tested (Zuber 1956: 180, figures 18-20; Stocks 1986; 1988: I, 17-99, II, 246-73). The tests indicated that stones of hardness Mohs 3, or below (including soft limestone), could effectively be cut with copper and bronze chisels and adzes. Stones harder than Mohs 3, including even calcite (Egyptian alabaster) had to be worked with different combinations of stone tools – pounders, hammers, picks, axes, chisels, punches, scrapers and sandstone rubbers. In addition to copper tools, stone implements were sometimes employed for shaping and smoothing soft limestone objects (Petrie 1938: 30)

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Preparing the surfaces of the Great Pyramid's limestone core- and casing-blocks was a two stage process. The average size of the blocks, according to W.M.F. Petrie (1883: 210, note) is 50 x 50 x 28 inches (1.27 x 1.27 x 0.71m). The *bottom* surfaces were already flattened and smoothed before inserting them into the structure of the pyramid (Edwards 1986: 283). The blocks' *top* surfaces were only made truly horizontal, flat and smooth after being fitted into the pyramid (Clarke & Engelbach 1930: 100): this system ensured that any block's top and bottom surfaces were parallel, essential for making each layer of blocks horizontal throughout the pyramid. The four vertical sides of a *core-block* were only roughly finished (Clarke & Engelbach 1930: 81), and not intended to fit closely to neighbouring blocks. However, abutting end-faces on *casing-blocks* formed tightly fitting rising-joints.

Ancient masons needed reliable tools for checking that the horizontal joint surfaces of all stone blocks were made accurately flat and truly horizontal, in addition to making flat and parallel the rising-joint surfaces of adjacent casing-blocks. Known instruments for testing horizontal and vertical surfaces all depend upon a hanging plumb line. Such instruments were the frame for testing horizontal planes, shaped like the letter "A", and the vertical testing frame, both made of wood. Models of the horizontal and vertical testing tools were found in the Nineteenth Dynasty (*c.*1315-1201 BC) tomb of the architect Senedjem at Deir el-Medina, an Upper Egyptian workers' village (Petrie 1917: 42, plate XLVII, B57, 59). The earliest plumb bobs (Petrie 1917: 42, plate XLVIII, B64, 65) date to the Third Dynasty (*c.*2687-2649 BC).

Calibrating a replica 'A' frame (Stocks 1988: II, 368) required the two bottom ends to touch the surface of still water, while simultaneously marking a vertical line on the horizontal bar exactly behind the hanging plumb line. This tool proved to be as reliable as a modern spirit level (Figure 1). A replica vertical testing tool was also constructed (Stocks 1988: II, 369). Provided the two horizontal pieces of wood were accurately made and fitted to the vertical piece, the tool's reliability also compared favourably with a spirit level (Figure 2). Although there is no direct evidence to prove that these two frames were in use at the Great Pyramid, the evidence for plumb lines predating the Fourth Dynasty and the ability of the masons to create truly horizontal and vertical surfaces at Giza do support the proposition.

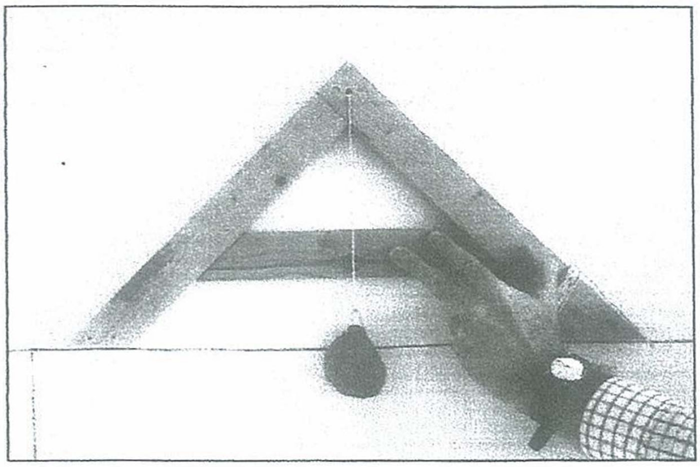

Figure 1. A replica 'A' frame and plumb line.

W.M.F. Petrie (1883: 213) and M.Z. Goneim (1956: 42) noticed red marks on stone masonry, and suggested that it had been rubbed with an accurate facing-plate smeared with red ochre to test a surface's flatness. Petrie (1909: 72) stated that a stone's surface was considered

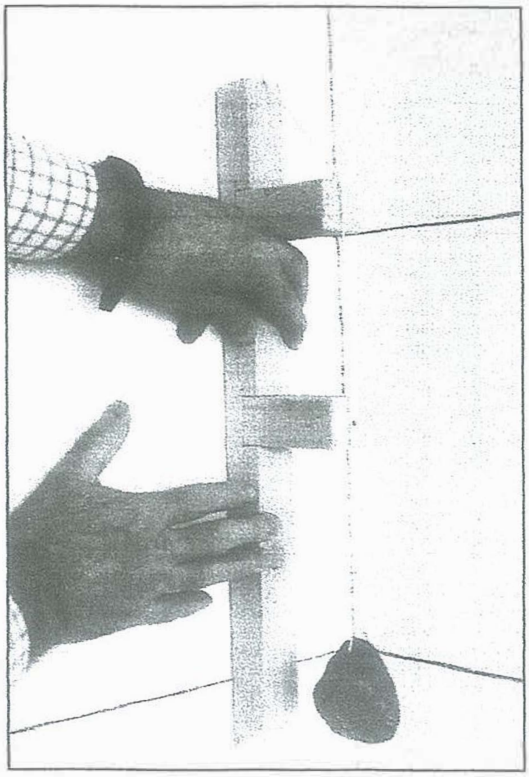

Figure 2. A replica vertical testing frame and plumb line.

flat enough if the red ochre touched the high points at intervals of not more than an inch (2.5cm). Besides these red ochre marks, there is no evidence to support the use of facing-plates for testing surface flatness in ancient Egypt. However, there is very good epigraphic and archaeological evidence for a simpler surface testing tool. A scene in the Eighteenth Dynasty (*c.* 1569-1315 BC) tomb of Rekhmire at Thebes, Upper Egypt (Davies 1943: II, plate LXII) shows two rods held upright against a block's perpendicular surface. A taut string connects the top of each rod. Two other rods are held against the string to check for high points on the stone. On a perpendicular surface, a taut string's slight sag, or catenary curve, acts towards the ground, whereas on a horizontal plane the string curves towards it, deceiving a mason into producing a concave surface.

Petrie (1890: 27, plate IX, 13) found a set of three rods at Twelfth Dynasty (*c.* 1991-1786 BC) Kahun, a workers' town near to the Fayum: the hole drilled into each of the outer rods is just large enough for a 2 mm-diameter string. Each rod (Petrie 1890: 27) measures 4.96 inches (12.6cm) in length, equal within two or three thousandths of an inch (0.005cm). How and why did a craftworker make the Kahun rods so accurate to one another? In the early 1880s, Petrie (1883: 44) measured the rising-joints separating several of the remaining large casing-blocks on the northern side of the Great Pyramid. He found that the mean variation of the cutting of the stone from a straight line and from a true square equalled 0.01 inch (0.25mm) up a joint 75 inches (1.90m) high. These joints, with an area of some 35 square feet (3.3m) each, were not only worked as finely as this, but also cemented throughout.

It is likely that both the core- and the casing-blocks' bottom and top surfaces were similarly prepared to this accuracy. Could the rods and string tool, by itself, have enabled ancient masons to flatten a stone block's surface to an accuracy of 0.25mm, and therefore to indicate the tool's use at Giza in the Fourth Dynasty? In trying to answer this question, a set of three replica rods was manufactured from a seasoned tree branch for testing (Stocks 1987: 45-6, figure 24; here Figure 3). Each rod was cut to the same length between two stones set firmly into the ground. This crude, yet effective, calliper ensured that the three rods matched each other in length. The accuracy of the Kahun rods points to the use of such a calliper. It did not matter that the actual lengths of the rods in units of measurement were unknown: extant rod sets do not conform to a standard measurement. For example, each rod in a Twelfth Dynasty set from Beni Hasan, Upper Egypt, measures 8.6cm in length (Petrie 1917: 42, plate XLIX, B49).

Each replica rod's length was checked with a modern instrument and all were equal within plus or minus 0.005cm. Two rods were drilled for the string. The experiments (Stocks 1987: 48-50) began by obtaining a horizontal surface, whose flatness was checked with a steel straight-edge. The test rods were stood upon this surface, with the string under considerable tension (Figure 3). Measurements indicated that test tensioned strings between 1.2 and 2m in length sagged by approximately 0.25mm, similar to the variation measured by Petrie on the base casing-blocks at Giza. Ancient masons may have used the rods and string tool, completely stretched out in a straight line, as an inside calliper for testing parallelism between the rising-joint surfaces of adjacent stone blocks, before fitting them into a building (Stocks 1987: 48, figure 25). Surface high spots could have been marked by a fingertip coated in red ochre (Stocks 1987: 48) – not necessarily by a facing-plate – when a rod was removed from its testing position next to the string. Subsequently, other masons dressed the high spots down, and as the work became closer to a flat surface, the spacing between the red ochre marks would decrease. In ancient times, a surface would be deemed flat when the third rod just touched the underside of the taut string along its length. Of course, a block's surface prepared in a horizontal position would end up slightly concave. However, the surface of a block actually shaped and tested in a vertical position, as illustrated in the tomb of Rekhmire, would not suffer such concavity.

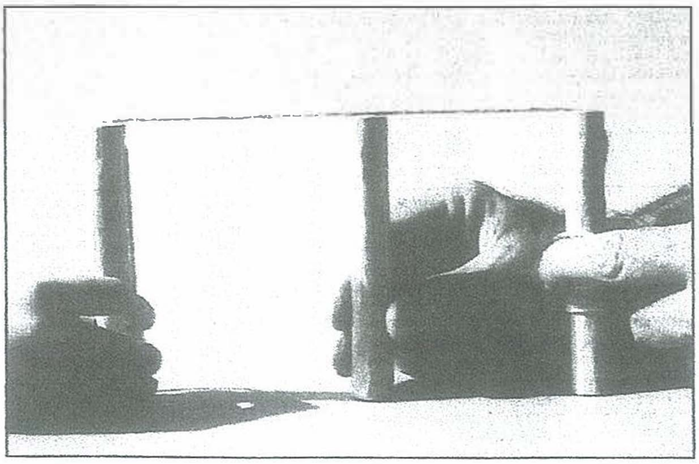

Figure 3. Demonstrating the replica Kahun rods and string.

Friction and force: moving the blocks into position

Friction between sliding surfaces of large blocks of limestone posed a serious problem to craftworkers moving them. The friction that must be overcome to move a block is proportional to the coefficient of friction μ and the normal force N (Timoshenko & Young 1956: 50). The coefficient of friction is a function of the type of surfaces in contact and the Normal force is the vertical force of gravity acting on the block. The force F required to move a block is $F = \mu N$. If F is taken as the force necessary to *start* sliding, μ is called the coefficient of static friction. (If F is taken as the somewhat smaller force necessary to *maintain* sliding, μ is called the coefficient of kinetic friction). The coefficient of static friction is the tangent of the angle of a ramp on which a block just starts to slide down. It can therefore be measured experimentally. It can be seen that the force required is independent of the areas in contact, and since the weight is fixed, the ease of moving a block can only be altered by altering the coefficient of friction, that is the character of the surfaces in contact. This what the Egyptians did.

In the Twelfth Dynasty tomb of Djehutihotep, at el-Bersheh, Upper Egypt (Newberry 1895: I, plate XV), there is an illustration of an alabaster statue of him, thought to weigh about 60 tonnes; which is being hauled along a level surface on a sledge by 172 men. A man is pouring some liquid, probably water, in front of the sledge's runners to maintain a muddy track to ease the friction. Once on a building, Egyptian masons' use of gypsum mortar as a sliding lubricant (Clarke & Engelbach 1930: 78-80) between blocks also significantly reduced the friction between the horizontal surfaces of one block and the one below. Automatically, and essentially, the filling of the slight spaces between imperfectly fitting horizontal joints with mortar prevented blocks from cracking, the mortar setting hard and evenly transmitting the load over supporting blocks' top surfaces (Clarke & Engelbach 1930: 78-9). This suggests that sledges lubricated with mud were used to transport the blocks to the pyramid and once laid on the course of stones, they would be moved on a layer of gypsum.

Since the surface area involved is not contributory to the force required, experiments were carried out to measure different coefficients of friction by masoning two small blocks of limestone to a tolerance of 0.25mm (one hundredth of an inch) (Figure 4). The prepared blocks' dry flat surfaces were placed in contact, one block above the other, the bottom block being slowly tilted until the top block just began to slide across its surface. The angle of tilt was 36 degrees. The tangent of this angle gives a coefficient of static friction of 0.73. The test was then repeated with liquid mortar applied to the bottom block's top surface. The upper block now commenced sliding at an angle of 8 degrees, giving a coefficient of static friction of 0.14. Another experiment revealed that a wooden sledge runner on liquid mud produced a similar coefficient of static friction.

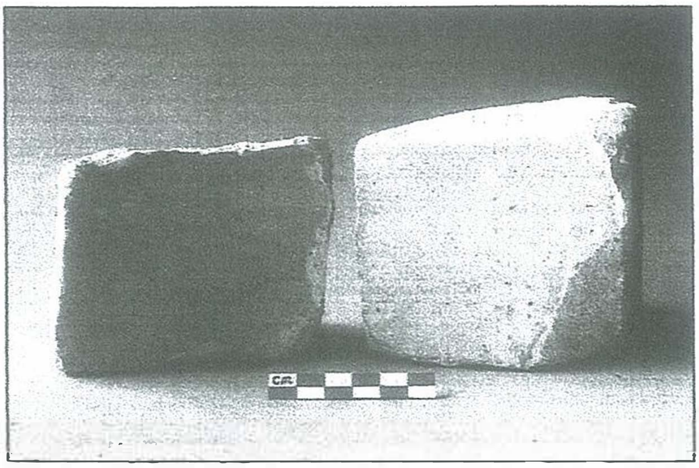

Figure 4. Two soft limestone blocks prepared for the dry and lubricated sliding tests.

Petrie (1883: 44) stated that a base casing-block positioned on the Great Pyramid's northern side weighed 'some 16 tons' (16 300 kg). To find the force, F, to start this block to slide dry on a flat and smoothed stone surface, its weight must first be converted to the Normal force, N, in Newtons, i.e., 16 300 x 9.8 = 159 740 Newtons. The sliding force, F, can now be calculated by multiplying the coefficient of static friction of 0.73 by the Normal force, N. F = 116 610 Newtons. To find the force, F, needed to start the same block sliding on a surface lubricated with liquid mortar, the lesser coefficient of static friction of 0.14 must be used, giving F = 22 363 Newtons. These results show that just over five times less force is needed to start a lubricated block moving than a similar dry block. This reduction factor applies to all blocks, no matter what their weight and area of surface contact.

The Djehutihotep illustration suggests that one worker was capable of initiating and maintaining a pulling force of about 500 Newtons (about 50 kg) in order to start the statue moving from rest. Therefore, about 45 workers could have started a lubricated 16 300 kg block moving on a horizontal surface. Once started, the force required to keep the block moving would drop, allowing it to be pulled forwards at a constant rate. A smaller, lubricated Great Pyramid casing-block of about 2750 kg would require an initial force of 3770 Newtons (about 385 kg). Eight workers could easily start a block of this weight moving on a level surface.

Hauling a block on a sledge up a slope, as would be required to fit it into a pyramid, required a balance between the force required and the angle at which slippage occurred. The force required to haul a block up a plane inclined at the angle of slippage is twice that required on the flat (Timoshenko & Young 1956: 162-7). This and the risk of losing a block through slippage means that the ramp should be inclined at less than the angle of slippage. This might explain why the angle of slope for some ancient ramps was less than eight degrees, the angle of slippage for a mud-lubricated sledge (above). For example, the gradient of a ramp left in the unfinished Fourth Dynasty mortuary temple of Menkaure at Giza is about one in eight, or just over seven degrees (Edwards 1986: 280). Also, two stone-built ramps excavated at the southern end of the Gebel el-Asr region, Lower Nubia (Shaw *et al.* 2001: 34), where gneiss was extracted from the quarries there, slope at seven degrees. Ramps sloping upwards at eight degrees and higher, are likely to have been used dry, it being both counter-productive and dangerous to lubricate such a ramp.

Conclusions

The experiments with the three replica surface-testing tools indicate their presence at Giza in the Fourth Dynasty: they, alone, could have enabled craftworkers to prepare the limestone blocks fitted into the Great Pyramid of Giza with the accuracy that has been observed. The sliding experiments revealed significant advantages in moving stone blocks, and loaded sledges, along mortar- and mud-lubricated horizontal surfaces, and suggest an optimum of around seven degrees for a lubricated ramp.

Acknowledgement

I sincerely thank Jeffrey Stocks for patiently explaining the laws of friction to me. However, the results obtained by applying these laws in the context of moving Fourth Dynasty limestone blocks at Giza are entirely my responsibility.

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Auf den Spuren von Cheops' Handwerkern

Bemerkungen zu Werkzeugen und Bautechniken bei der Errichtung der Großen Pyramide von Giza

Denys Stocks

Foto: Michael Haase

Im Oktober 2004 wurden die Nachbauten dreier altägyptischer Meßwerkzeuge getestet, mit denen die Ebenheit der Oberflächen und die Anordnung von Kalksteinblöcken überprüft werden konnten, die in der 1. Steinlage an der Nordseite der Cheops-Pyramide eingepaßt sind. Außerdem konnte eine »gestreifte« Werkzeugspur an einer Innenwand von Cheops' Granitsarkophag nachgewiesen werden, die frühere Hinweise bestätigt, daß der Sarkophag mit kupfernen Röhrenbohrern ausgehöhlt wurde (siehe hierzu auch Sokar 6, S. 41ff.).

Übersetzung aus dem Englischen von Christine Mende

Die aus der 4. Dynastie stammende Pyramide des Cheops (ca. 2609–2584 v. Chr.) stellt einen Höhepunkt des altägyptischen Pyramidenbaus dar. Bei der Errichtung dieses Grabmals wurden Werkzeuge und Techniken eingesetzt, die es erlaubten, die großen Kalksteinblöcke für das Kernmauerwerk und die Verkleidung mit einem außergewöhnlichen Grad an Genauigkeit zu verlegen, um die Stabilität des Bauwerks zu gewährleisten. Aber diese wichtigen Techniken des Pyramidenbaus wurden nicht in kurzer Zeit entdeckt. Sie sind das Resultat eines etwa 85–90 Jahre lang währenden Lernprozesses, der mit der in der 3. Dynastie errichteten Stufenpyramide des Djoser (ca. 2686–2668 v. Chr.) in Sakkara begann.

Bevor sich das Bauen in Stein vollständig etabliert hatte, wurden die Mastabas aus Lehmziegeln errichtet. Erst Djosers Stufenpyramide besteht aus grob behauenen Kernblöcken aus Kalkstein, die in ihrer Form den Lehmziegeln nachgebildet waren, jedoch größer dimensioniert sind (siehe Fotos rechts). Die Verkleidungsblöcke wurden dagegen viel sorgfältiger bearbeitet. Sie besaßen geglättete Ober- und Unterseiten; die senkrechten Seitenflächen der Blöcke hatte man allerdings nur bis zu 5 cm hinter den Frontseiten der Quader akkurat angepaßt. Die Verkleidungssteine der Knickpyramide des Snofru (4. Dynastie, ca. 2649–2609 v. Chr.) sind größer als die bei Djoser und nicht nur akkurat an den Ober- und Unterseiten, sondern auch an den seitlichen Oberflächen geglättet worden (siehe Foto S. 5 oben links). Bei Snofrus Roter Pyramide in Dahschur, dem unmittelbaren Vorgängerbau der Großen Pyramide von Giza, passen sich die noch erhaltenen Verkleidungsblöcke ebenfalls genau in dieses Bearbeitungsschema ein.

Autorenprofil

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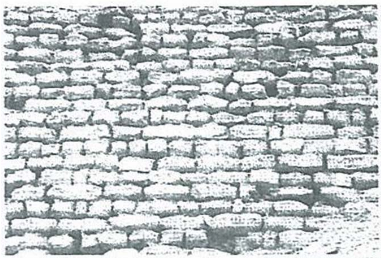
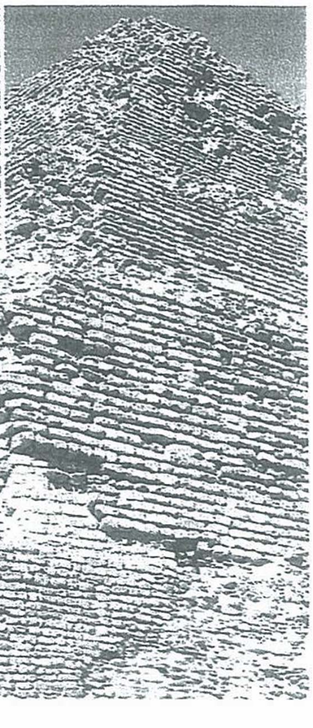


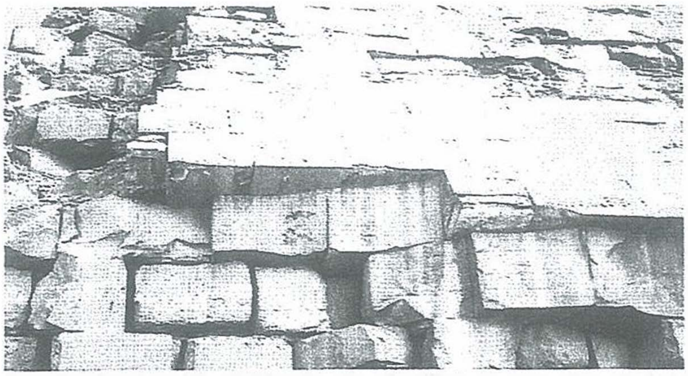
Detailaufnahme der Steinblöcke des Kernmauerwerks der Stufenpyramide des Djoser.

Foto: Michael Haase



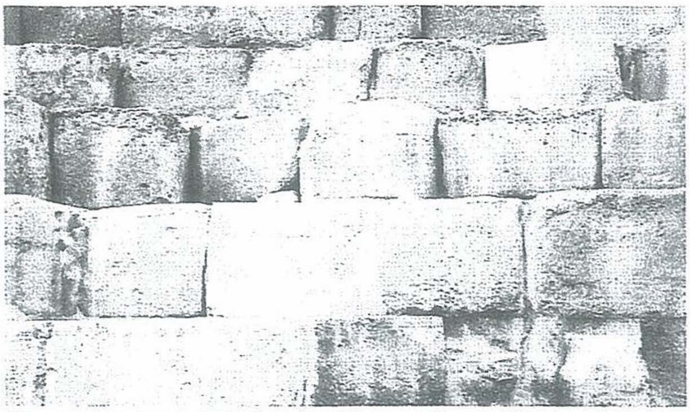
Blick auf die Süd-Ost-Ecke der Stufenpyramide des Djoser in Sakkara.

Foto: Paul Stocks



Im Bereich der Nord-West-Ecke der Knick-Pyramide: Akkurat bearbeitete Verkleidungsblöcke aus Tura-Kalkstein.
Foto: Paul Stocks

Blick auf den mittleren Bereich der Ostseite der Roten Pyramide mit den noch erhaltenen Lagen der Verkleidung.
Foto: Michael Haase



Kernmauerwerksblöcke der Cheops-Pyramide aus lokalem Kalkstein. Foto: Denys Stocks

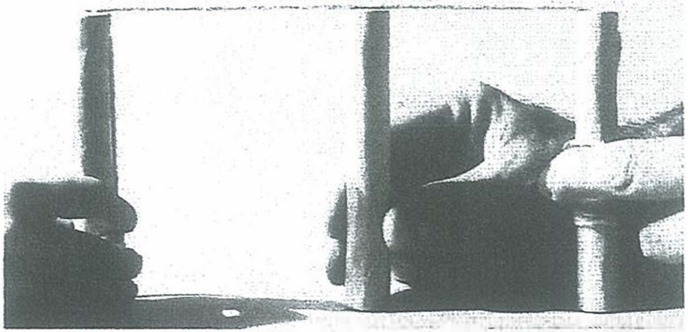
Die Genauigkeit der Oberflächen von Kernmauerwerks- und Verkleidungsblöcken der Cheops-Pyramide

In den frühen 1880er Jahren hat Sir Flinders Petrie[1] die senkrechten Fugen einiger der erhaltenen Verkleidungsblöcke an der Nordseite der Großen Pyramide von Giza vermessen (siehe Fotos S. 7 oben). Er fand heraus, daß z. B. die mittlere Abweichung der 1,90 m langen Fugen von einer geraden Linie nur 0,25 mm beträgt. Diese speziellen Fugen an den Blockseiten, die eine Fläche von ungefähr 3,3 m² aufweisen, wurden aber nicht nur fein ausgearbeitet, sondern sind auch durchweg mit Gipsmörtel versetzt worden. Der Mörtel reduzierte u. a. die Reibung beim Schieben eines Blockes über einen anderen erheblich. Später, als sich der Mörtel in den (auch noch so kleinen) Zwischenräumen zwischen den Blöcken verhärtet hatte, verhinderte er, daß Risse auftraten.

Cheops' Bauleute wußten, daß die Ober- und Unterseiten der Kernmauerwerks- und Verkleidungsblöcke sorgfältig vorbereitet und kontrolliert werden mußten, um die Stabilität der Pyramide zu gewährleisten. Die vier Seiten eines Kernmauerwerkblocks wurden nur grob bearbeitet,[2] denn es war nicht beabsichtigt, sie genau an die Nachbarblöcke anzupassen. Jedoch mußten die Frontseiten zu den aneinandergrenzenden Verkleidungsblöcken präzise angeglichene senkrechte Fugen bilden. Die Unterseiten der Kalksteinblöcke des Kernmauerwerks wie auch die der Verkleidung der Cheops-Pyramide sind akkurat abgeflacht und geglättet worden, *bevor* sie in das Mauerwerk der Pyramide eingefügt wurden.[3] Die Oberseiten der Blöcke sind allerdings erst *nach* dem Einpassen in den Pyramidenstumpf nivelliert und geglättet worden.[4] Dieses System stellte sicher, daß die Ober- und Unterseiten der Steinblöcke parallel lagen. Dies war unerläßlich, um jede Steinlage innerhalb der Pyramide horizontal und eben zu verlegen.[5]

Drei Werkzeuge für die Überprüfung der Blockoberflächen

Das antike Werkzeug zur Überprüfung der ebenen Beschaffenheit von Steinblockoberflächen bestand aus drei senkrechten Stangen: zwei von ihnen waren durch eine Schnur verbunden, die gespannt war; die dritte Stange wurde ihrer Länge nach gegen die Schnur gehalten, um den Stein auf Unebenheiten zu prüfen (Foto unten). Auf einer senkrechten Oberfläche[6] hing das gespannte Seil etwas in Richtung Boden, der Abstand zur zu bearbeitenden Steinoberfläche blieb aber gleich, während das Seil auf einer horizontalen Fläche leicht durchhing, so daß bei der Nachbearbeitung eine leicht konkave Fläche entstehen konnte.[7] Petrie[8] fand einen Satz derartiger Stangen in Kahun (12. Dynastie). Zwei von ihnen hatten an je einem Ende eine Bohrung für eine Schnur von 2 mm Durchmes-



Oben: Nachbau eines altägyptischen Meßgerätes zur Bestimmung der Ebenheit von Steinoberflächen. Es besteht aus drei gleichlangen Holzstangen, von denen zwei mit einem Seil verbunden sind. Foto: Jeffrey Stocks

Rechts: Zeichnung des Meßgerätes. Abb.: Denys Stocks

Umzeichnung einer Abbildung aus dem Grab des Rechmire in Theben-West: Steinmetze bei der Prüfung einer senkrechten Oberfläche eines Steinblocks und bei der Nachbearbeitung. Abb.: Denys Stocks, nach Norman de Garis Davies, Band II, Tafel LXII

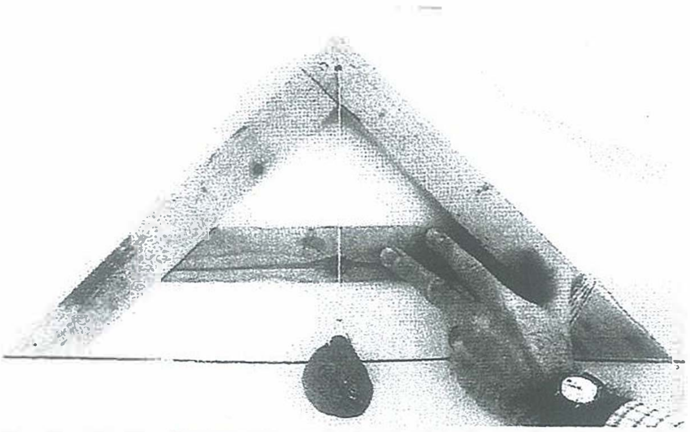
ser. Die Vermessung der Stangen ergab, daß sie alle 12,6 cm lang waren (mit einer Ungenauigkeit von nur 0,005 cm).

Die bekannten Werkzeuge,[9] die es den antiken Steinmetzen ermöglichten, horizontale und vertikale Oberflächen herzustellen, enthalten alle eine Lotschnur. Es sind hölzerne Konstruktionen, die in der Form der Buchstaben »*A*« und »*F*« aufgebaut sind. Mit dem A-förmigen Gestell, einer sogenannten »*Lotwaage*« (oder »*Setzwaage*«, siehe Foto rechts oben), konnte man horizontale Flächen, mit der F-förmigen Holzkonstruktion, eine Art »*Richtlot*« (siehe Foto unten), vertikale Oberflächen überprüfen. Modelle dieser beiden Werkzeuge sind im Grab des Architekten Senedjem in Deir el-Medina (Theben-West) aus der 19. Dynastie gefunden worden. Aus Meidum stammende Steingewichte für die Lotschnüre, die in die 3. Dynastie datiert werden,[10] deuten auf die Möglichkeit hin, daß derartige Werkzeuge bereits vor der Errichtung der Cheops-Pyramide in Gebrauch waren.

Ein Satz von drei Stangen zur Bestimmung der ebenen Beschaffenheit einer Steinoberfläche wurde zu Testzwecken hergestellt.[11] Jede Stange konnte in ihrer Länge durch zwei Steine justiert werden, die fest im Boden fixiert waren. Diese einfache, jedoch effektive Schieblehre stellte sicher, daß die drei Stangen gleich lang waren, was automatisch die Genauigkeit des Werkzeugs gewährleistete. Die einheitliche Länge der Stangen aus Kahun zeigt, daß diese einfache konstruktive Technik den ägyptischen Steinmetzen bekannt gewesen war. Die Längen der nachgebildeten Stangen wurden mit einer Schublehre überprüft; sie sind mit einer Ungenauigkeit von lediglich 0,005 cm alle gleich lang. Zwei Stangen wurden für die Schnur durchbohrt. Es konnte gezeigt werden, daß zugbeanspruchte Seile mit einem Durchmesser von 2 mm bei einer Länge zwischen 1,2 m und 2 m etwa um 0,25 mm durchhängen[12] – ähnlich der Abweichung, die Petrie an den Verkleidungsblöcken der Großen Pyramide gemessen hatte.

Um die Genauigkeit einer nachgebauten »*Lotwaage*«[13] zu bestimmen, war es erforderlich, daß die beiden unteren Enden des »*A's*« eine unbewegte Wasseroberfläche berührten, während die Lotschnur gleichzeitig die vertikale Linie auf der horizontalen Stange markierte. Als dieses Werkzeug zusammen mit einer modernen Wasserwaage auf einer flachen Oberfläche getestet wurde, erwies es sich als genauso präzise wie die Wasserwaage selbst.

Ein F-förmiges »*Richtlot*« wurde ebenfalls nachgebaut.[14] Vorausgesetzt, die beiden horizontalen Leisten, die an der langen vertikalen Holzleiste befestigt waren, hatten die gleiche Länge, so war die Zuverlässigkeit dieses Werkzeugs zur Prüfung vertikaler Oberflächen ebenfalls mit der einer Wasserwaage vergleichbar.



Nachgebaute »Lotwaage«, mit der die Horizontale einer Steinoberfläche festgestellt werden kann. Foto: Jeffrey Stocks

Überprüfung der Genauigkeit der Oberflächen von Kernmauerwerks- und Verkleidungsblöcken der Cheops-Pyramide

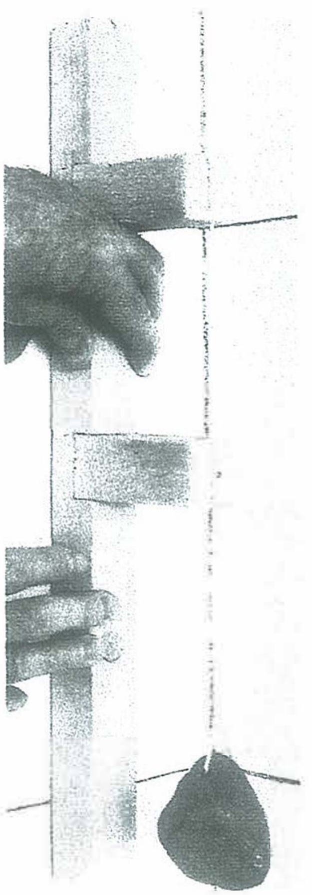
Zusammen mit der nachgebauten »*Lotwaage*« wurden die nachgebildeten Stangen und das Seil benutzt, um die Genauigkeit der oberen Flächen von zwei benachbarten Blöcken des Kernmauerwerks in der 1. Steinlage an der Nordseite der Cheops-Pyramide zu untersuchen (siehe Fotos rechts). Diese Blöcke sind 1,45 m hoch und ihre Oberseiten liegen frei. Obwohl die Oberflächen ein wenig angegriffen sind, konnte durch die Tests mit Stangen und Seil (die dritte Stange berührte gerade noch die Unterseite des gespannten Seils) ermittelt werden, daß die Oberseiten eines jeden Blocks (mit einer Ungenauigkeit von 0,25 mm) noch immer eben sind. Jedoch wäre eine leichte Wölbung, die sich aus dem Gebrauch des Meßwerkzeugs ergeben hätte, um zu einer solchen Genauigkeit einer ebenen Oberfläche zu führen, von den antiken Bauleuten nicht bemerkt worden.

Ein weiterer Test, bei dem man die eine Stange auf die Mittelachse der Oberfläche eines Steinblocks und die andere Stange auf die des danebenliegenden Blocks stellte, zeigte, daß beide Oberflächen mit einer Genauigkeit von 0,25 mm bearbeitet wurden.

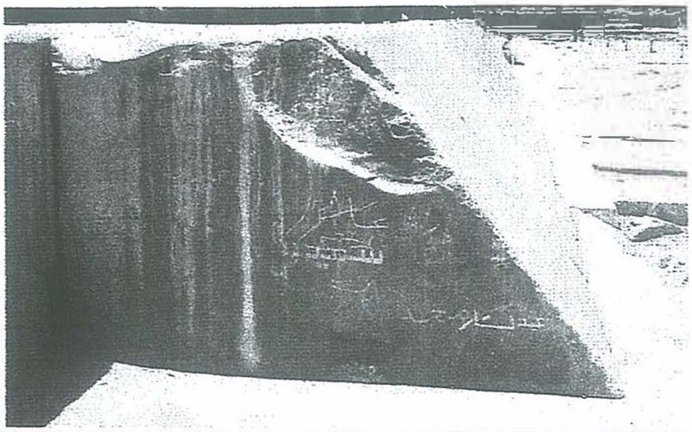
Auch die freiliegende, linke Seitenfläche eines Verkleidungsblocks, der nahe des Pyramideneingangs in der 1. Lage an der Nordseite liegt (siehe Foto S. 7 rechts oben), wurde mit Stangen und Seil auf ihre Ebenheit überprüft. Die Oberfläche ist überall auf bis 0,25 mm genau bearbeitet worden.

Die Überprüfung der Oberflächen der zwei benachbarten Blöcke des Kernmauerwerks auf ihre waagerechte Lage hin mit Hilfe der nachgebauten »*Lotwaage*« zeigte, daß die Lotschnur genau auf der Markierung der horizontalen Leiste saß. Die Tests haben also schlüssig bewiesen, daß diese beiden Blöcke eben und horizontal sind – so, als wären sie genau aneinander ausgerichtet worden.

Bei der freiliegenden seitlichen Oberfläche des Verkleidungsblocks berührte die Lotschnur des F-förmigen Holzgestells beide horizontalen Leisten, was darauf hinweist, daß sie noch genau senkrecht ist.



Nachbau eines altägyptischen Werkzeugs zur Prüfung der Vertikalen (»Richtlot«). Foto: Jeffrey Stocks



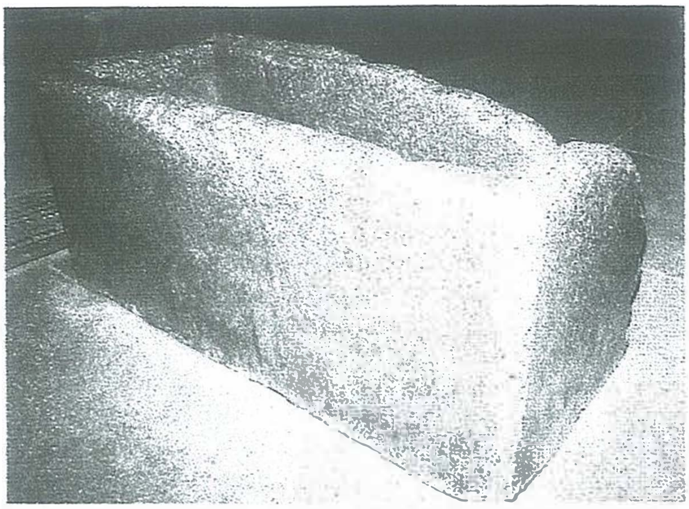
Rechts: Verkleidungsblock aus Tura-Kalkstein an der Nordkante der Cheops-Pyramide, westlich unterhalb des originalen Zugangs ins Grabmal (siehe Pfeil Foto unten). Messungen der Genauigkeit der senkrechten Seitenoberfläche haben ergeben, daß sie überall auf 0,25 mm genau bearbeitet wurde. An der Basis des Steinblocks erkennt man eine halbkreisförmige Vertiefung, die als Ansatzpunkt für einen stabilen Holzhebel diente, mit dem der schwere Block von der Seite an seine Position geschoben wurde. Foto: Michael Haase

An der Nordseite der Cheops-Pyramide. Oben die Sparrenkonstruktion über dem originalen Zugang ins Grabmal, in der Mitte der Eingang des Grabräuberganges. An der Basis die noch erhaltenen Verkleidungsblöcke aus Tura-Kalkstein.

Foto: Michael Haase

Die Werkzeugspur im Rosengranit-Sarkophag des Cheops

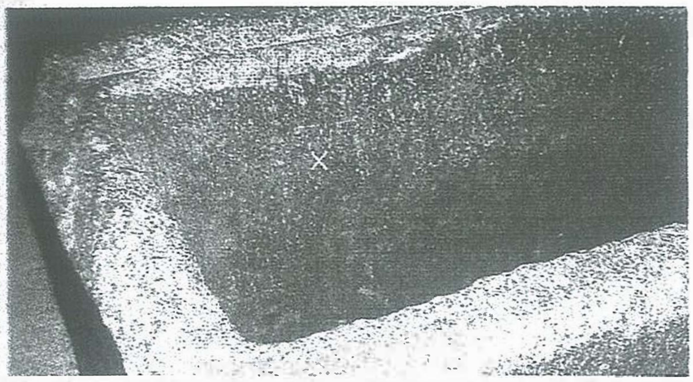
Ebenfalls in den frühen 1880er Jahren hat Sir Flinders Petrie[15] eine bogenförmige Markierung in der Ostseite der Innenwand des Sarkophags des Cheops vermessen. Diese Markierung ist 2,54 mm tief, 7,6 cm hoch und 3,3 cm breit. Unter Anwendung eines schwachen Lichtstrahls, der unter einem extrem schrägen Winkel auf die Markierung schien, ergab die derzeitige visuelle Auswertung horizontale Streifen entlang ihrer gesamten Länge – vergleichbar mit denen, die bei einer experimentellen Bohrung in Rosengranit mittels eines kupfernen Röhrenbohrers und unter Zuhilfenahme von Sand als Schleifmittel erzielt werden konnten.[16] Das untere Ende der Markierung liegt 21,3 cm unterhalb der oberen Kante des Sarkophags[17] und stellt wahrscheinlich die maximale ursprüngliche Eindringtiefe des Röhrenbohrers infolge entgegenwirkender Reibungskräfte dar.



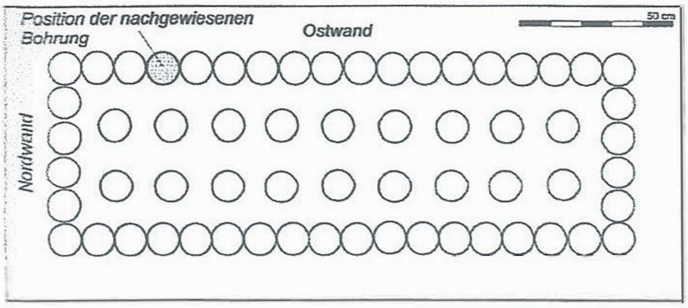
Die Sarkophagwanne aus Granit in der Grabkammer der Cheops-Pyramide. Blick von Südwesten. Foto: Michael Haase

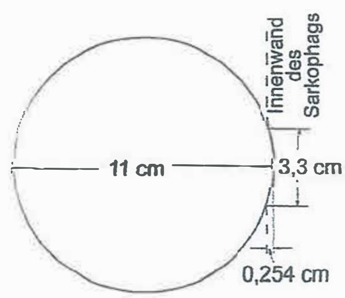
Unter Berücksichtigung von Petries Messungen haben trigonometrische Berechnungen ergeben, daß ein kupferner Röhrenbohrer mit einem Durchmesser von 11 cm (dies entspricht ungefähr sechs altägyptischen Fingern oder anderthalb Handbreiten) für die Bohrung in Granit benutzt worden ist.[18] Weitere Berechnungen zeigten, daß eine Röhre mit 11 cm Durchmesser fast genau 18mal in die Länge des Innenraums des Sarkophags von 198,3 cm (26,5 Handbreiten) paßt und sechsmal in die Breite von 68,1 cm (9 Handbreiten).[19] Dieser Befund wird durch den Sarkophag Sesostris' II. (12. Dynastie, Mittleres Reich) aus Illahun bestätigt.[20] Eine Röhre mit dem gleichen Durchmesser von 11 cm paßt dort entsprechend genau 19mal bzw. sechsmal in die innere Länge von 209,5 cm (28 Handbreiten) bzw. Breite von 67,4 cm (9 Handbreiten).[21]

Petrie hat die Entfernung der Mittelachse der bogenförmigen Markierung zur inneren nördlichen Wand nicht aufgezeichnet: Die Untersuchung ergab eine Länge von 37,5 cm. In einer gedachten Linie von 18 Bohrlöchern entlang der östlichen



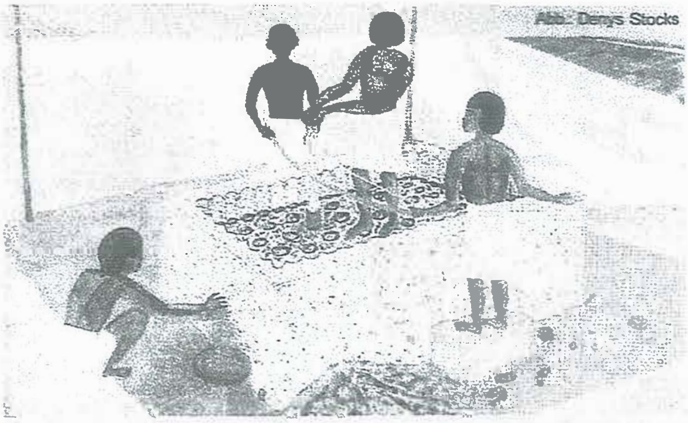
Position der Spur eines Röhrenbohrers an der östlichen Innenwand des Sarkophags des Cheops. Foto: Michael Haase





Oben: Schema der Ausbohrung des Innenraumes des Sarkophags des Cheops nach Denys Stocks. Abb.: Michael Haase, nach Denys Stocks

Links: Umriß einer Bohrung im Sarkophag des Cheops. Abb.: Denys Stocks



Zeichnung, die altägyptische Handwerker beim Ausbohren eines Granitsarkophags mittels eines Röhrenbohrers zeigt.

1999: Bohrversuche in Granitblöcken in Assuan mittels eines kupfernen Röhrenbohrers. Foto: Denys Stocks

Innenseite des Sarkophags liegt die berechnete Mittelachse des 4. Loches 38,5 cm von der Nordwand entfernt (die entsprechenden Mittelachsen des 3. und 5. Loches bei 27,5 cm und 49,5 cm). Unter Berücksichtigung von Ungenauigkeiten (es wurde z. B. nicht genau senkrecht gebohrt) liegt die gemessene Entfernung von 37,5 cm nahe der Position des berechneten 4. Loches (siehe Abb. oben), was den Gebrauch eines Bohrers mit 11 cm Durchmesser beim Aushöhlen von Cheops' Sarkophag auf diese Art und Weise bestätigt.

Der kupferne Röhrenbohrer mit einem Durchmesser von 11 cm (wie er bei Cheops' Sarkophag zur Anwendung kam) wurde wahrscheinlich aus mehreren Gründen zu einem Standardbohrer. Erstens wurde bei experimentellen Bohrungen in Rosengranit mit einem kupfernen, im Durchmesser 8 cm großen Röhrenbohrer gezeigt, daß drei Arbeiter ihn mit einem großen Bogen (unter Zuhilfenahme von Sand als Schleifmittel)[22] bis zu 120 mal in der Minute im und gegen den Uhrzeigersinn drehen konnten. Allerdings machten diese Experimente auch deutlich, daß ein Team von drei Bohrern bei einem Röhrenbohrer mit einem deutlich größeren Durchmesser als 11–12 cm Schwierigkeiten beim Drehen haben würde. Das ist zurückzuführen auf das Schleifmittel aus Sand am flachen Bohrkopf der Röhre und die Trägheit, die sich durch das Gewicht der Röhre und den hölzernen Bohrstiel entwickelt. Zweitens hat ein Bohrer (mit einem Durchmesser von 11 cm) ein günstiges Verhältnis zwischen dem ausgebohrten Stein und dem Volumen des Bohrlochs, nachdem man den Kern entfernt hat. Drittens stellt ein ungefähr 10–10,5 cm dicker Kern den wahrscheinlich größten Durchmesser dar, der mit einem einzigen Arbeitsgang mittels eines flach zugespitzten Meißels, den man in den sich verjüngenden Bohrschlitz steckt, herausgebrochen werden kann. Diese Methode war bei der vollständigen Entfernung eines 7,5 cm dicken Kerns in einem Stück aus einem Bohrschlitz mit 8 cm Durchmesser wirkungsvoll: Der Kern brach unter großer Spannung an seiner Basis. Jedoch ist es unwahrscheinlich, daß ein mehr als 10 cm dicker Kern mit Hilfe dieser Methode in einem Stück herausgebrochen werden kann. Das Rohr selbst ist als Hebel nicht geeignet (auch nicht bei Kernen mit einem Durchmesser von 7,5 cm), da sich das weiche Kupferrohr verformt hätte.

Schlußfolgerung

Die Benutzung von drei antiken Werkzeugen zum Prüfen einer Oberfläche bestätigte die beobachtete Genauigkeit und Ausrichtung der Oberflächen von mehreren Kernmauerwerks- und Verkleidungsblöcken der Großen Pyramide, was darauf hindeutet, daß die antiken Steinmetze diese einfachen, aber sorgfältig hergestellten Werkzeuge benutzen, um die Kalksteinblöcke der Cheops-Pyramide in Giza einzupassen.

Die Position einer Markierung, die von einem Röhrenbohrer an der inneren Ostwand des Granitsarkophags des Cheops hinterlassen wurde, trägt dazu bei, daß bezüglich der Bohrmethoden, die bei der Aushöhlung dieses Sarkophags angewendet wurden, sicherere Einschätzungen gemacht werden können. Die Abmessungen der Markierung (zusammen mit der Bewertung vorhergehender experimenteller Rohrbohrungen in Rosengranit) legen nahe, daß der Durchmesser des Bohrers (11 cm), der für die Aushöhlung des Sarkophags des Cheops benutzt wurde, eine Standardgröße für diese Art Bohrvorgang wurde.

Anmerkungen:

[1] Petrie, Temples and Pyramids, S. 44.*

[2] Clarke/Engelbach, S. 81.

[3] Edwards, S. 283.

[4] Clarke/Engelbach, S. 100.

[5] Stocks, Stoneworking, S. 194; Stocks, Great Pyramid, S. 573.

[6] Davies, Band II, Tafel LXII. Die Steinmetze haben die vertikale Oberfläche eines Steinblocks vermutlich in Abwärtsrichtung geprüft.

[7] Stocks, Stoneworking, S. 191.

[8] Petrie, Kahun, Gurob and Hawara, S. 27, Tafel IX, 13. Heute Katalognummer 28 des Manchester Museum.*

[9] Siehe CM JE27258 (»Lotwaage«) und CM JE27260 (»Richtlot«). Zur Anschauung siehe Petrie, Tools, Tafel XLVII, B57, 59.

[10] Siehe Petrie, Tools, S. 42, Tafel XLVIII, B64, 65.

[11] Stocks, Egyptian tool, S. 46, Abb. 24.

[12] Stocks, Great Pyramid, S. 575.

[13] Stocks, Industrial technology, S. 368; Stocks, Stoneworking, S. 180, S. 182, Abb. 7.2 und 7.3.

[14] Stocks, Industrial technology, S. 369; Stocks, Stoneworking, S. 180, S. 182, Abb. 7.2 und 7.3.

[15] Petrie, Temples and Pyramids, S. 84.*

[16] Stocks, Aswan, S. 91ff.

[17] Petrie, Egyptians, S. 93.*

[18] Stocks, Industrial technology, S. 148ff., Abb. 23 und 24.

[19] Stocks, Industrial technology, S. 920, Abb. 2.

[20] Petrie, Illahun, Kahun and Gurob, S. 3f.

[21] Stocks, Industrial technology, S. 151.

[22] Stocks, Aswan, S. 91f., Abb. 2 und 3.

* Petries Messungen wurden in das metrische System umgerechnet.

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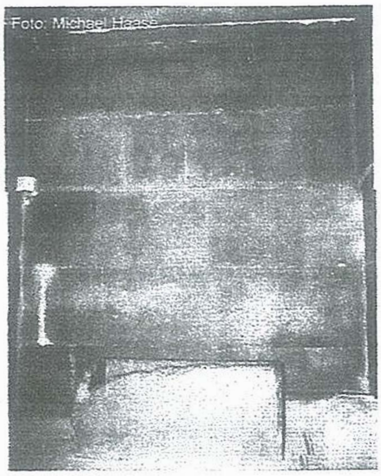
Mein aufrichtiger Dank gilt Dr. Zahi Hawass, Generalsekretär des Supreme Council of Antiquities in Ägypten, für seine freundliche Genehmigung zur Durchführung dieser Untersuchungen an der Cheops-Pyramide in Giza. Außerdem danke ich dem Discovery Channel und Edgework Media (Washington DC) für die Möglichkeit, diese Forschungen betreiben zu können sowie für ihre freundliche Genehmigung, daß ich sie für diesen Artikel benutzen durfte. Besonderer Dank gebührt auch Richard Wells, Heike Wells, Jack Turner und Paul Stocks für ihre Hilfe und Unterstützung an der Cheops-Pyramide.

ABSTRACT

In October 2004, an opportunity arose to use replicas of three ancient Egyptian measuring tools to check the surface accuracy and alignment of several limestone blocks fitted into the lowest course of the northern side of the Great Pyramid of Giza. Also, the position of a striated tool mark left in Khufu's rose granite sarcophagus is established, supporting previous indications as to how this artefact was hollowed with copper tubular drills.

Siehe auch den Hinweis auf das Buch von Denys Stocks auf S. 63.

Wann wurde der Sarkophagdeckel aus der Cheops-Pyramide entfernt?



Im westlichen Bereich der Grabkammer der Großen Pyramide von Giza steht eine aus einem einzigen Granitblock herausgearbeitete Sarkophagwanne, in der einst die sterblichen Überreste des Cheops lagen (Foto links). Die äußeren Maße der Granitwanne (2,28 × 0,99 × 1,05 m) zeigen, daß der Sarkophag nicht durch die Korridore transportiert werden konnte, sondern bereits während der Errichtung der Grabkammer dort aufgestellt wurde. Sein Standort ca. 1,35 m von der Westwand entfernt gewährleistete, daß westlich des Sarkophags ausreichend Platz für den Aufbau eines stabilen Gerüstes vorhanden war, mit dem der etwa 1,2 t schwere und heute nicht mehr vorhandene Sarkophagdeckel bis zur Bestattung des Königs in einer erhöhten Position gehalten und letztlich über die Granitwanne geschoben werden konnte.

An der westlichen Oberkante der Sarkophagwanne befinden sich drei kleine Bohrlöcher, die vermutlich einst zylinderförmige Stifte aufnehmen konnten, mit denen der Deckel (nachdem man ihn entlang einer keilförmigen Nut über den Innenraum schob) fixiert und der Sarkophag somit verriegelt wurde. Einen ähnlichen Befund weist auch der Granitsarkophag in der Pyramide des späteren Königs Chephren auf. Chephrens Sarkophag wurde jedoch in das Bodenpflaster der Grabkammer eingelassen, was die Handhabung bei seinem Verschließen mit dem Deckel vereinfachte (s. Foto S. 29 unten).

Der Verbleib des Deckels des Cheops-Sarkophags kann anhand schriftlicher Überlieferungen auf ein relativ kleines Zeitintervall eingegrenzt werden: Im Jahr 1512 betrat Zaccaria Pagani, ein Mitglied einer diplomatischen Gesandtschaft aus Venedig, die Grabkammer der Cheops-Pyramide und hielt später für die Nachwelt fest: »*Man erblickte dort einen Sarkophag (...), der bedeckt ist, aber leer.*«[1] Der Sarkophagdeckel befand sich demnach noch in der Grabkammer; er lag offenkundig auf der Granitwanne. Hingegen berichtete der Arzt und Naturforscher Prosper Alpini im Jahr 1591, daß der Deckel nicht mehr vorhanden war.[2] Demzufolge muß er im Lauf des 16. Jahrhunderts von irgend jemanden aus der Pyramide entfernt worden sein. Der Verdacht fällt insbesondere auf den damaligen Vizekönig von Ägypten, Ibrahim Pascha, dessen Arbeiter 1584 den Grabräubertunnel (Foto unten) auf der Suche »*nach einem Schatz*« in der Pyramide vergrößern ließen, »*so daß man darin aufrecht stehen kann*«.[3] Wofür der Granitdeckel benötigt wurde, ist unbekannt. Vermutlich ist er zertrümmert worden und die Fragmente wurden als »Schmuckelemente« oder kleinere Bauteile weiterverarbeitet. *Michael Haase*

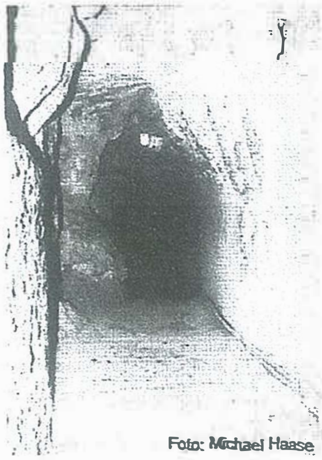


Foto: Michael Haase

Anmerkungen/Literatur:

[1] aus Lauer, J.-P., Das Geheimnis der Pyramiden, 1980, S. 32.

[2] siehe Lauer, S. 36.

[3] aus Lehner, M., Das Erste Weltwunder, 1997, S. 43; siehe auch Lauer, S. 36.

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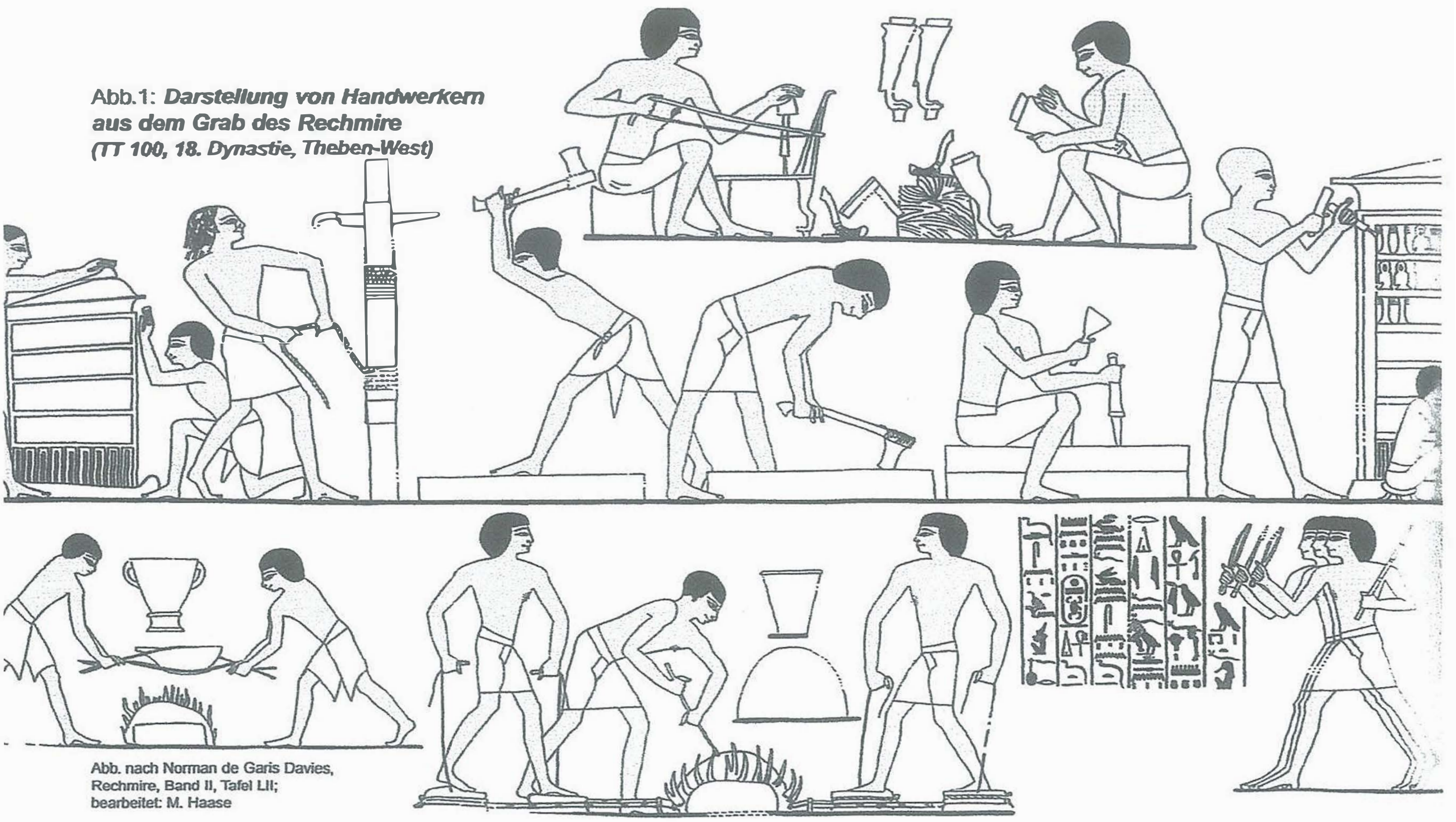


Abb.1: ***Darstellung von Handwerkern aus dem Grab des Rechmire*** *(TT 100, 18. Dynastie, Theben-West)*

Abb. nach Norman de Garis Davies, Rechmire, Band II, Tafel LII; bearbeitet: M. Haase

Werkzeugkonstrukteure im Alten Ägypten

DENYS STOCKS

Über einen Zeitraum von Tausenden von Jahren errichteten altägyptische Handwerker spektakuläre Bauwerke aus Stein und verarbeiteten viele Materialien zu den unterschiedlichsten Objekten. All diese Bauwerke und Gegenstände mußten einerseits entworfen werden; andererseits benötigte man qualifizierte Handwerker, die über Werkzeuge verfügten, die jede arbeitstechnische Schwierigkeit bewältigen konnten. Diese Handwerker entwickelten und fertigten aber nicht nur die uns heute bekannten Werkzeuge wie z. B. Meißel, Beile, Sägen, Messer oder Äxte, sondern sie konstruierten auch spezielle Geräte für besondere Aufgaben. Was waren das für spezielle Werkzeuge? Wie wurden sie gefertigt und wie funktionierten sie?

Aus dem Englischen von CHRISTINE MENDE

Aus Untersuchungen vorhandener antiker Werkzeuge, durch Studien der Geräte, die in Gräbern abgebildet, aber nicht von Archäologen gefunden werden konnten, und durch Spuren an vollendeten und unvollendeten Objekten, die von Werkzeugen verursacht wurden, für die es keine archäologischen Belege gibt, geht klar hervor, daß es im alten Ägypten über die Jahrtausende hinweg eine stetige Entwicklung in der Werkzeugkonstruktion gegeben hat. Einige Geräte sind Kopien vorhandener Werkzeuge gleicher Bauart, die aus neuen Materialien geformt wurden. Andere Werkzeuge wurden aus modifizierten Pflanzenstämmen hergestellt. Weitere Geräte sind sogar zu hochentwickelten Fertigungssystemen ausgebaut worden, die eine Serienproduktion mit sich wiederholenden Abläufen ermöglichten. Wieder andere Werkzeuge wurden so entworfen, daß es möglich war, abgenutzte Teile zu ersetzen, ohne das gesamte Werkzeug erneuern zu müssen (z. B. Geräte, die mit auswechselbaren Bohrspitzen ausgestattet worden sind).

AUTORENPROFIL
***DENYS STOCKS** (Manchester); Highschool-Lehrer i. R., beschäftigt sich seit 1977 mit der theoretischen und experimentellen Erforschung altägyptischer Handwerkstechniken.*

Kopien vorhandener Werkzeuge aus neuen Materialien

Meißel, Beile, Sägen, Messer und Äxte

Der Einsatz von geschmolzenem und gegossenem Kupfer in der prädynastischen Epoche (ca. 3600 v. Chr.) erlaubte es den Handwerkern, die Formen bereits vorhandener Werkzeuge zu kopieren. Diese Auffassung wurde zuerst von WILLIAM M. FLINDERS PETRIE im Jahr 1917 vertreten.[1] In Anlehnung an PETRIES Vorschlag ist es wahrscheinlich, daß sich z. B. der Feuersteinschaber[2] zu einem Kupfermeißel und dem gleichartig geformten Axtblatt, die gezackten Feuersteinsicheln und -messer[3] zu den gezackten kupfernen Holzsägen, die glattkantigen Feuersteinmesser[4] zu Kupfermessern und die steinernen Faustkeile[5] zu mit Griffen ausgestatteten Kupferäxten weiterentwickelt haben.

Obwohl kupferne und bronzene Schneidwerkzeuge von großer Bedeutung waren, konnten sie lediglich Holz und weiche Steinarten wie weichen Kalkstein, roten Sandstein, Gips und Speckstein bearbeiten.[6] Feuerstein war in prädynastischen wie auch dynastischen Zeiten das vorrangige Material für Werkzeuge, um die härtesten Steine zu bearbeiten. Vertiefte Reliefs in Granit wären z. B. ohne Meißel, Schlägel und Schaber aus Feuerstein nicht machbar gewesen. Mit rekonstruierten Feuersteinwerkzeugen[7] konnten Werkzeugspuren reproduziert werden, die in vielen antiken Artefakten aus weichem und hartem Stein gefunden wurden.

Die meisten antiken Kupfermeißel und Axtklingen sind doppelseitig spitz zulaufend gehämmert (eine beidseitig schräge Fläche) und auf beiden Seiten geschärft, womit diese Werkzeuge zum gewaltsamen Zerkleinern von Holz und weichen Steinarten optimal geeignet sind (Abb. 2). Einige Meißel und Breitbeile sind auf der einen Seite flach und nur auf der anderen, schrägen Seite geschärft – also einseitig spitz zulaufende Werkzeugklingen, die außerordentlich nützlich zum Schneiden und Abschälen von Holz und weichem Stein sind.

Der Rohrbohrer und die Gesteinssäge

Vor ca. 3600 v. Chr. diente der Stamm des einfachen hohlen Schilfrohres, das entlang des Niltals im Übermaß wuchs, als Rohrbohrer, der, wenn er zusammen mit trockenem Sand als Schleifmittel verwendet wurde, in der Lage war, Löcher in Steinobjekte wie Keulenköpfe aus Schiefer, Kalzit oder hartem Kalkstein zu bohren. Die Rekonstruktionen haben aber auch gezeigt, daß Schilfrohrbohrer keine härteren Steine als diese bohren können (Abb. 3).[8] Vorausgesetzt der hohle Bereich des Schilfrohres ist lang genug, um mit einem Strick eines Bogens umschlossen oder mit den Händen im und gegen den Uhrzeigersinn gedreht zu werden, so erfüllt er alle Voraussetzungen eines Bohrers. Ein Rohrbohrer erzeugt einen röhrenartigen Einschnitt, der einen zentralen Kern umschließt. Diese Technik ermöglicht es, daß beim Bohren nur eine kleine Menge des Steins entfernt werden muß, man aber nach dem Herausbrechen des Kerns ein vollständiges Loch erhält.

Abb. 3: ***Testbohrung von weichem Sandstein mit einem Schilfbohrer und Schleifmittel aus Sand.***
Foto: Jeffrey Stocks

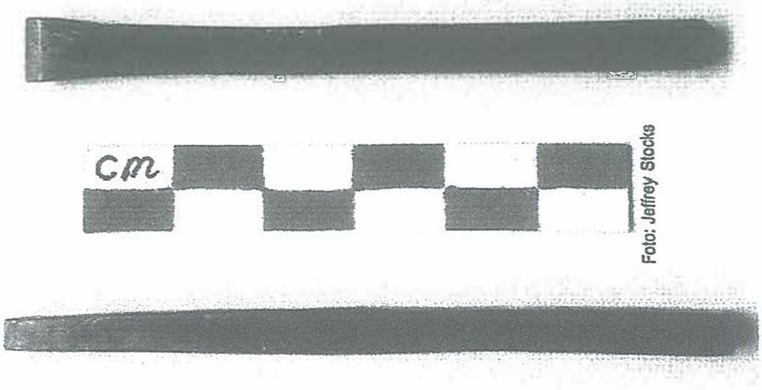


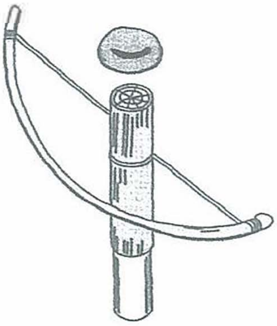
Foto: Jeffrey Stocks

Abb. 2: ***Die Nachbauten zweier kupferner Meißel.***

Nach der Einführung der Kupferguß-Technik etwa 3600 v. Chr. waren die prädynastischen Handwerker in der Lage, den Schilfrohrbohrer in Kupfer nachzubauen. Hierfür wurde eine Platte aus dickem, gegossenem Kupfer mittels eines Steinhammers auf einem steinernen Amboß dünner geschlagen. Anschließend hat man sie zu einer Röhre gerollt[9] und diese unter Zuhilfenahme eines Schleifmittels gedreht. Kerben auf dem runden Schaft des Bohrers nahmen ein Bogenseil auf und ermöglichten es, den Bohrer mittels eines Bogens rotieren zu lassen (Abb. 4). Dabei konnte er mit Hilfe eines Handgriffes im und gegen den Uhrzeigersinn gedreht werden.

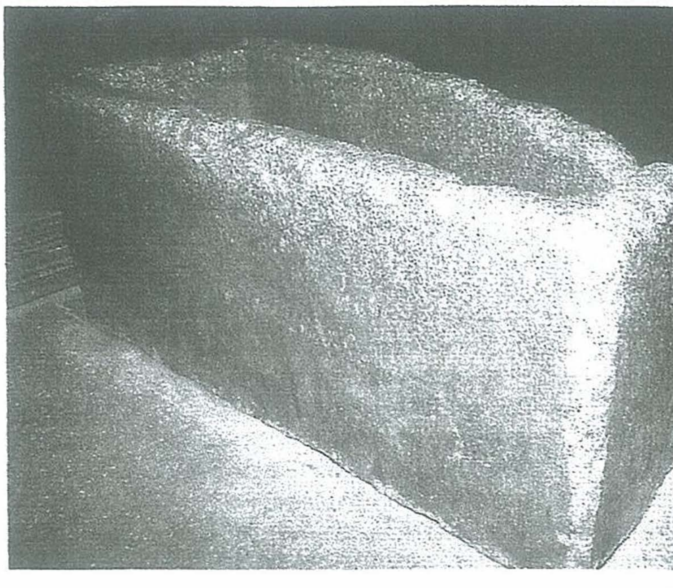
Eine geschlagene Kupferplatte, die nicht gerollt wurde, brachte hingegen die flexible, flachkantige Steinsäge hervor, die ebenfalls mit Schleifmittel benutzt werden konnte.

Der Kupferbohrer und die flachkantige Säge erlaubten es, alle Hartgesteine zu bohren und zu sägen – z. B. Granit, Porphyr, Diorit und Basalt. Experimente mit rekonstruierten Werkzeugen haben die Schnittleistung und Verluste an Kupfer durch Abnutzung der Geräte verifizieren können.[10]



<< Abb. 4:
Darstellung eines Röhrenbohrers.
Abb. nach Denys Stocks; bearbeitet: M. Haase

Abb. 5, unten:
Die Sarkophagwanne aus Granit in der Grabkammer der Cheops-Pyramide. Blick von Südwesten.
Foto: Michael Haase



Der kupferne Röhrenbohrer machte es den Handwerkern viel einfacher, spätzeitliche Vasen aus Hartgestein wie auch in dynastischen Zeiten Sarkophage aus diesen Materialien auszuhöhlen. Die Steinsäge ermöglichte es, Granitsarkophage in Form zu bringen – allen voran den Sarg des Cheops in dessen Grabmal auf dem Giza-Plateau (4. Dynastie, Abb. 5). Schilf, Kupfer- und Bronzebohrer und flachkantige metallene Steinsägen erwiesen sich als leistungsfähige Werkzeuge zum Bohren und Sägen in Stein.

Werkzeuge aus abgewandelten natürlichen Materialien

Der Bogen zum Antrieb eines Werkzeugs

Der ägyptische Bogen zum Antrieb von Feuer-, Holz-, Steinperlen- und Röhrenbohrern wurde hauptsächlich wie ein angewinkelter menschlicher Arm (mit einem Winkel am Ellbogen) geformt.[11] Um ihn herzustellen, mußte ein Zweig von einem sich verzweigenden Ast eines Baumes abgeschnitten und der leicht gebogene Schaft geglättet werden. Einschnitte in jedem Ende nahmen die Sehne des Bogens auf. Beim Gebrauch wurde der Bogen am kürzeren der beiden gewinkelten Teile angefaßt.

Damit der Bogen Bohrwerkzeuge antreiben konnte, mußte das ungefähr 2 mm dicke Bogenseil einmal um den Schaft des Bohrers gewickelt werden. Dazu war es notwendig, daß das Seil eine bestimmte Länge hatte. Das brachte automatisch Spannung in das Seil, was bei dem gehärteten, steifen Bogenschaft Biegekräfte hervorrief. Verschiedene nachgebaute Bogen zeigten diese Charakteristik.[12] Ein halbkugelförmiger Stein, der auf der unteren Seite ausgehöhlt war, diente als Abdeckung, in der sich das obere Ende des Werkzeugs drehen konnte, während das untere Ende des Werkzeugs in das Material schnitt. Der eingefettete Deckstein erlaubte es dem Handwerker, Druck auf den Bohrer auszuüben, während er diesen kräftig mit dem Bogen bewegte. Bogen zum Antrieb von Werkzeugen wurden wechselseitig hin und her bewegt, wobei das Bogenseil diese Bewegung in eine Drehung umsetzte.

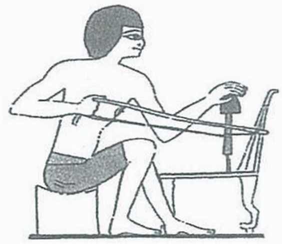


Abb. 6: ***Darstellung aus dem Grab des Rechmire (Theben-West): Handwerker beim Bohren von Holz.***
Abb. nach Norman de Garis Davies, Rechmire, Band II, Tafel LII; bearbeitet: M. Haase

Blasrohre für Schmelzöfen und Gebläse mit Fußbedienung

Altägyptische Arbeiter entwickelten zwei Methoden für den Betrieb von Schmelzöfen. In der prädynastischen Zeit formten Handwerker ein hohles Schilfrohr zu einem langen Blasrohr für ihre Schmelzöfen. Dazu stießen sie einen schmaleren, angespitzten Stock durch das Schilfrohr und drückten dadurch die bis dahin getrennten Fasern aneinander. An dem Ende des Blasrohres, das später in den Schmelzofen gehalten werden sollte, wurde eine Spitze aus getrocknetem Ton festgemacht.

Experimente mit einem rekonstruierten Blasrohr zeigten, daß einem Schmelzofen pro Minute 50 Liter Luft zugeführt werden konnten.[13] In Grabmalereien sind bis zu sechs Arbeiter abgebildet (Abb. 7), die Luft in einen Schmelzofen blasen.[14] Das sind weitaus mehr als die 200 Liter Luft pro Minute, die benötigt wurden, um 1 kg Kupfer in einem Tiegel zu schmelzen.

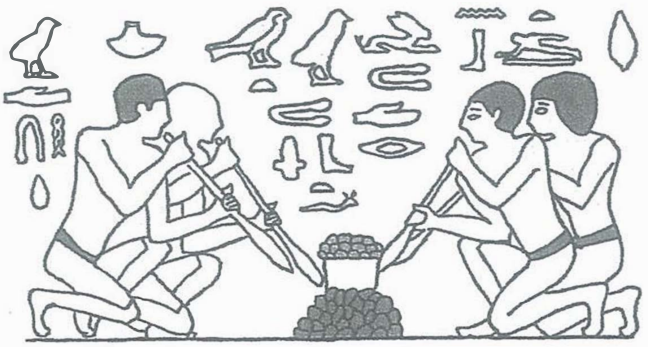


Abb. 7: ***Darstellung von Metallarbeitern aus der Mastaba des Wepemnofret (5. Dynastie). Vier Männer, die zu zweit an je einer Seite eines Schmelztiegels sitzen, fachen mit Blasrohren das Feuer an, um dadurch den Schmelzprozeß zu unterstützen.***
Abb. nach Selim Hassan, Excavations at Giza II, Fig. 219; bearbeitet: M. Haase

In der 18. Dynastie kamen Gebläse mit Fußbedienung in Gebrauch. Solche Gebläse sind in den thebanischen Gräbern von Rechmire (Abb. 1), Pujemre, Nebamun und Ipuki dargestellt.[15] Sie bestehen aus zwei nebeneinander plazierten, flachen Tonschüsseln, die jeweils mit einer beweglichen Membran aus Leder überspannt sind, welche straff an den Rändern befestigt ist. In der Mitte jeder Membran ist ein langes Seil fixiert. Seitlich an jeder Schüssel befindet sich ein hohles Schilfrohr, dessen Mündung aus Ton in Richtung des Schmelzofens zeigt. Um die Gebläse zu bedienen, stand ein Arbeiter mit jeweils einem Bein auf den Schüsseln. Er trat abwechselnd mit einem Fuß auf eine der Membranen und zog gleichzeitig die andere Membran mit dem Seil hoch, während er dort den anderen Fuß anhob. Ein natürlicher »Laufrhythmus« sicherte einen steten Zufluß an Luft durch die Schilfröhren. Ein rekonstruiertes Gebläse konnte mit einiger Übung genügend Luft zuführen, um 1 kg Kupfer zu schmelzen.[16]

Der dreibeinige »Amboß«

Metallhandwerker benutzten handliche kugel- und halbkugelförmige Steinhämmer, um Metallgefäße in Form zu klopfen, welche (wie im Grab des Rechmire in Theben-West dargestellt) umgekehrt auf einem dreibeinigen Amboß plaziert wurden.[17] Nimmt man die Abbildung als Vorlage, be-

Abb. 8: *Ein rekonstruierter dreibeiniger »Amboß« zum Bearbeiten von großen und kleinen Steingefäßen.*
Foto: Jeffrey Stocks

Foto: Jeffrey Stocks

<< Abb. 9: ***Aushöhlen einer Kalksteinvase mit einem rekonstruierten Bohrer (mit einem kupfernen Zylinder).***

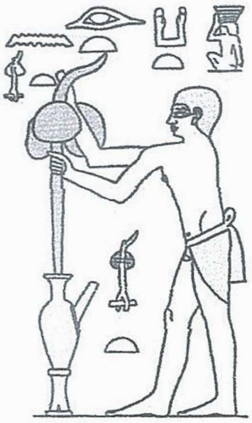


Abb. 10: ***Ein Handwerker beim Ausbohren eines Gefäßes mittels eines Kurbelbohrers. Umzeichnung einer Darstellung aus dem Grab des Ti in Sakkara.***

Abb.: Michael Haase, nach G. Steindorff, Tafel 134

steht der Amboß aus einem gegabelten Ast, dessen gespaltenes Ende spitzwinklig auf den Boden gestellt wurde (Abb. 8).[18] Durch ein schräg aufwärts gebohrtes Loch im oberen, einfachen Ende dieses Astes wurde eine lange hölzerne Stange gesteckt. Dieser Stab diente nicht nur als drittes Bein für den Amboß, sondern konnte je nachdem, ob große oder kleine Gefäße bearbeitet wurden, innerhalb der Loches justiert werden. Das Gewicht eines Gefäßes auf diesem Dreibein hielt die Teile zusammen. Die Stabilität war gewährleistet, da jedes dreibeinige Objekt relativ sicher auf unebenem Grund stehen kann.

Modifizierte Werkzeuge mit austauschbaren Teilen

Der Drehbohrer

Das erste auswechselbare Werkzeugsystem, der Drehbohrer, ist in verschiedenen Gräbern aus dynastischer Zeit dargestellt,[19] wobei jedoch bislang keiner von ihnen gefunden werden konnte. Seine Einführung fand vermutlich in später prädynastischer Zeit statt, nachdem die Herstellung von Kupferröhren aus gegossenem Kupfer gelungen war. Mit diesem Werkzeug konnten Steingefäße ausgehöhlt werden.

Das Werkzeug bestand aus einem langen, runden Bohrschaft, an dem ein spitz zulaufendes, gewinkeltes Oberteil oder ein Griff angebracht war. Wie bei einem Bogen ist dafür ein gegabelter Ast eines Baumes abgesägt und geglättet worden. Am unteren Ende des Bohrschaftes wurde dann ein kupferner Bohrkopf angebracht. In früheren Dynastien hatte man den Griff mit zwei Steinen, in späteren Dynastien mit einem einzigen schweren Stein beschwert.

Nach dem Bohrvorgang schnürte man einen gegabelten Stiel, dessen Enden an der gegabelten Seite auf die gleiche Länge gekürzt worden sind, am unteren Ende des Bohrschaftes fest. Die Gabel konnte kleinere und größere, achtförmige Bohrköpfe aus Stein aufnehmen. Mit diesen hatte man das bereits vorgebohrte Loch erweitert, so daß bauchige Gefäße im Inneren weiter ausgehöhlt werden konnten. Der Drehbohrer trieb außerdem halbmondförmige Bohrköpfe aus Feuerstein und Hornstein an, um Gefäße aus weichem Gestein auszuhöhlen. Konische Bohrköpfe wurden hingegen benutzt, um den Hals eines Gefäßes zu weiten und zu formen. In Feldversuchen konnte mit derartig rekonstruierten Werkzeugen eine Vase aus Kalkstein hergestellt werden (Abb. 9).[20]

Das Design eines Drehbohrers erhöhte sein Drehmoment, also den Kraftaufwand, der teilweise für die Drehung des Bohrers benötigt wurde. Aufgrund der Gleitfähigkeit des Seils übertragen Bögen aber weniger Drehmoment auf den drehenden Schaft und sind daher bei großem Widerstand (bedingt durch die Reibung) nicht geeignet dafür, um Bohrköpfe aus halbmondförmigem Feuerstein oder Steinen anzutreiben.

Im Laufe der Zeit nutzte sich der festgeschnürte gabelförmige Ast ab, konnte aber durch einfaches Abschnüren durch einen neuen ersetzt werden. Das Hauptwerkzeug, das aus dem Drehschaft und dem Handgriff sowie dem Steingewicht bestand, mußte dabei nicht ersetzt werden. Frühe Versionen des Drehbohrers werden in Illustrationen als ein einziger gegabelter Schaft dargestellt. Sobald dieser Schaft abgenutzt war, mußte das gesamte Werkzeug ersetzt werden. Der kupferne Bohrkopf sowie die verschiedenen Bohrköpfe aus Stein nutzten sich ebenfalls ab, aber auch diese konnten leicht durch neue ersetzt werden.

Der zusammengesetzte werkzeughaltende Bohrstab

Geräte zum Feuermachen wurden von William M. Flinders Petrie im Kahun der 12. Dynastie gefunden.[21] Die Hilfsmittel bestanden aus einem Deckstein, einem Holzklotz, einem Bogen und einem Feuerbohrer (Abb. 11). Der Klotz ist mit mehreren Löchern ausgestattet worden. Die Löcher waren an den Kanten durchgebrochen oder eingekerbt, um zu ermöglichen, daß glimmender Holzpuder in den Zunder fallen konnte.

Der Feuerbohrer aus Kahun besitzt keinen konstanten Durchmesser, sondern verjüngt sich zu einem schmaleren Mittelstück. Bei Gebrauch rotierte das obere Ende in einem Deckstein und das untere Ende drehte sich in einem Loch, das in den Holzklotz gebohrt wurde. Die Experimente mit den nachgebauten Kahun-Geräten zeigten,[22] daß die antiken Feuerbohrer wahrscheinlich aus hartem Holz gefertigt waren, während die Klötze aus weichem Holz bestanden. Die Herstellung eines speziell geschnitzten Feuerbohrers war eine zeitaufwendige Angelegenheit, und die Versuche machten deutlich, daß ein Hartholzbohrer sich während des Gebrauchs langsam abnutzte. Früher oder später wurde

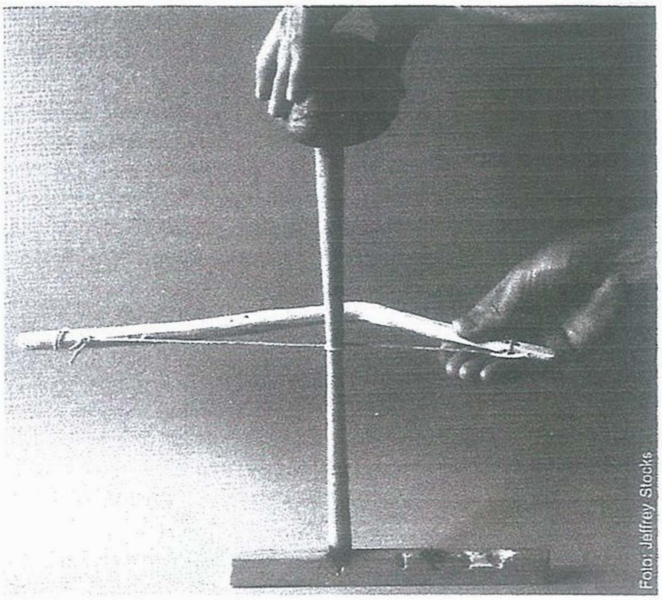


Abb. 11: ***Erprobung eines rekonstruierten Feuerbohrers.***

Foto: Jeffrey Stocks

der abgenutzte Feuerbohrer unbrauchbar und mußte ersetzt werden.

Die Lösung der antiken Handwerker für dieses Problem konnte von Petrie ebenfalls in Kahun gefunden werden. Er entdeckte einen taillierten hölzernen Bohrstab; einen weiteren aus der 18. Dynastie fand er in Ghurob.[23] Auch Howard Carter entdeckte einen Bohrstab im Grab des Tutanchamun (18. Dynastie) in Theben.[24] Das untere Ende dieses Bohrstabes war glatt und nach oben hin mit einem kleinen, zentral angebrachten Loch durchbohrt. In diesem Loch des Bohrstabes des Tutanchamun befand sich ein kurzer, gerader Feuerbohrer.

Das obere Ende des Kahun-Bohrstockes, das als Stift geschnitzt war, rotierte in einer hölzernen Kappe. Am unteren Ende war der Stock durch ein vertikales Loch ausgehöhlt, das nicht nur Feuerbohrer, sondern auch Kupferbohrer und kleine Feuersteinbohrer aufnehmen konnte. Diese Werkzeugteile konnten herausgenommen und ausgetauscht werden, indem man sie mit einem dünnen Stock aus diesem Loch herausschob. Der Stock wurde dafür an einer seitlich angebrachten schrägen Aussparung am Bohrstab angesetzt, die mit dem oberen Ende des senkrechten Loches verbunden war.

Die Experimente mit einem nachgebauten Bohrstab machten deutlich,[25] daß, sobald sich das Bogenseil aufgrund der heftigen Bewegung des Bogens spannte, sich sein Halt auf dem taillierten Stab lockerte. Wenn jedoch das Bogenseil an einem dickeren Bereich des Stabes angesetzt wurde, straffte sich das Seil automatisch, solange die Bohrung andauerte.

Die technischen Veränderungen zu einem werkzeughaltenden Drehstock bestätigen die Praxis, daß der Austausch sich während des Bohrens abnutzender Teile (wie gegabelte Äste, Kupferrohre und steinerne Bohrköpfe im Fall des Drehbohrers sowie Feuer-, Holz- und Feuersteinbohrer im Falle des werkzeughaltenden Drehstocks) notwendig war, um das Hauptwerkzeug zu erhalten, in das immerhin eine beträchtliche Menge Zeit und Energie investiert wurde.

Werkzeuge, die wissenschaftliche und mechanische Grundsätze verbinden

Schraubstock mit Gegengewicht

Ein interessantes technisches Gerät, das mit einer gezahnten Kupfersäge zusammen benutzt wurde, ist in einigen Gräbern abgebildet – vor allem in denen der 12. Dynastie in Meir und Deshasheh.[26] Die Apparatur besteht aus einem vertikalen, in den Boden eingelassenen Pfahl, an dem das obere Ende eines langen Stück Holzes mit einem losen Seil befestigt ist (Abb. 12). In die Aussparung des Seils zwischen dem Pfahl und dem Stück Holz wird ein kräftiger Ast (als Hebel) gesteckt und so lange gedreht, bis er sich in einer horizontalen Position befindet und das Seil fest gespannt ist. Der Ast wird dann mit Hilfe eines steinernen Gegengewichts, das mittels eines Seils am freien Ende des Stabes befestigt wird, in dieser Position gehalten. Dieses Werkzeug erlaubte es den antiken Handwerkern, aus dem befestigen Stück Holz Planken zu sägen.

Experimente mit Ast, Gegengewicht und Seil[27] haben gezeigt, daß diese Vorrichtung durch das Gegengewicht das Seil zusätzlich spannt. Wird das Gegengewicht vollständig abgesenkt, verliert das Seil seine Spannung. Das Gerät fungiert demnach wie ein Schraubstock, den man schnell lokkern kann, wenn das Holz am Pfahl hochgeschoben werden soll, um den Sägevorgang fortzusetzen: Beide Hände sind frei, um die Säge zu halten und damit eine größere Kraft bei ihrer Benutzung anwenden zu können. Zum Vergleich: Der Schaduf benutzt ebenfalls ein Gegengewichthebel, um bei der Anhebung von Wasser von einer niedrigen auf eine höhere Ebene eine größere Wirkung zu erzielen.

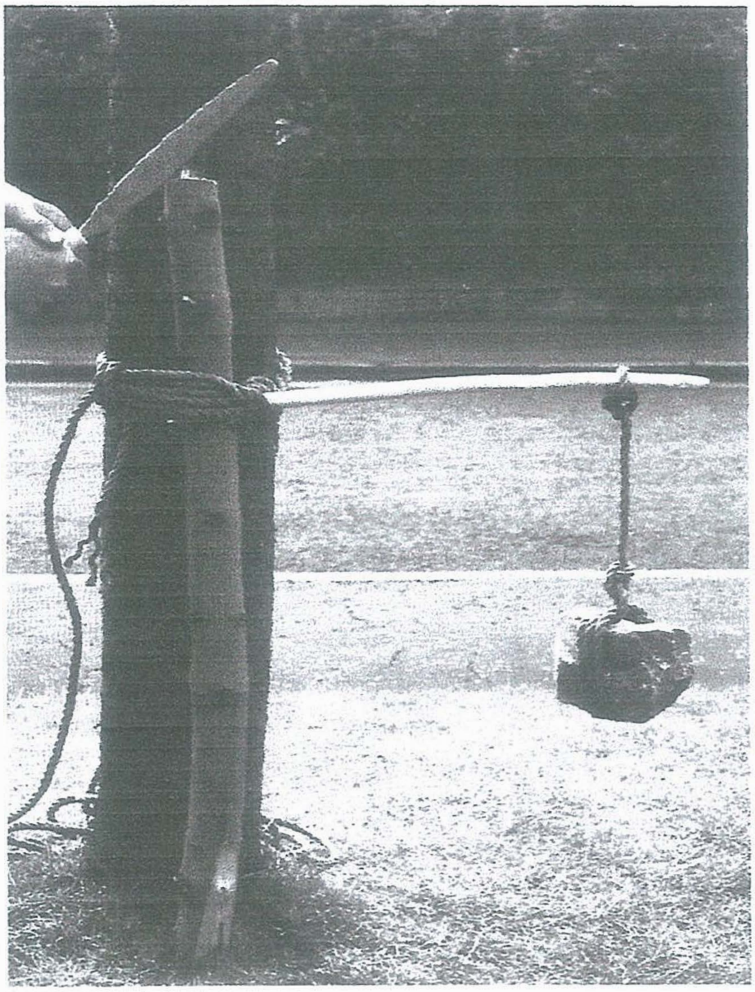


Abb. 12: ***Der rekonstruierte »Schraubstock« mit Gegengewicht ermöglicht das Sägen mit beiden Händen.***

Foto: Jeffrey Stocks

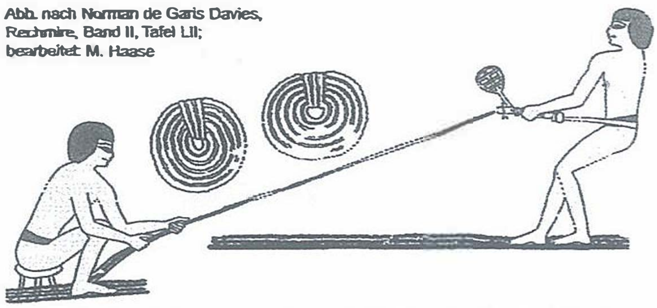


Abb. nach Norman de Garis Davies, Rechmire, Band II, Tafel LII; bearbeitet: M. Haase

Abb. 13: ***Darstellung aus dem Grab des Rechmire (18. Dynastie, Theben-West): zwei Arbeiter beim Drehen eines Seiles.***

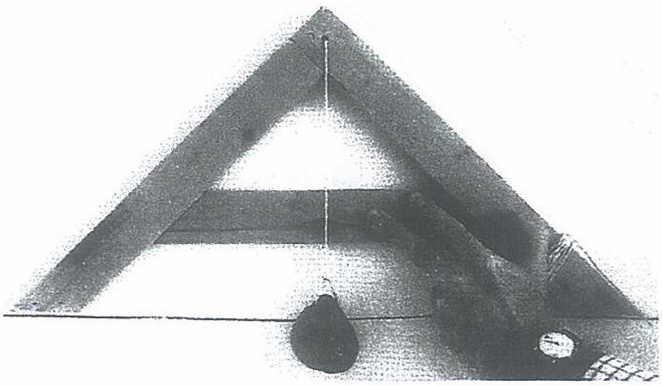


Abb. 14: ***Nachgebaute »Lotwaage«, mit der die Horizontale einer Steinoberfläche festgestellt werden kann.*** Foto: Jeffrey Stocks

Werkzeug zum Drehen von Garn

Schnüre und Seile wurden aus verschiedensten natürlichen Materialien wie Kamelhaar, Elefantengras, Flachs und Dattelpalmfasern wie auch aus Leinen, Papyrus und Leder hergestellt. Der erste Schritt umfaßte die Herstellung von Garn aus Fasern, die alle in die gleiche Richtung gedreht wurden. Anschließend sind die Garne in der anderen Richtung umeinander gedreht worden, um ihre Festigkeit zu erhöhen.

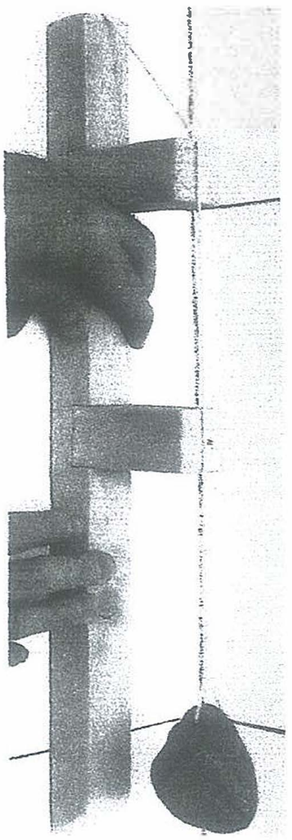
Im Grab des Rechmire in Theben[28] zeigt eine Darstellung zwei Arbeiter, die ein Seil herstellen (Abb. 13). Während der eine mehrere Fäden umeinanderlegt, sind die anderen Enden dieser Fäden an einer Holzleiste befestigt, das an einer Art Gürtel des anderen Arbeiters angebracht ist. An dieser Leiste befindet sich eine Holzstange, an deren Ende mittels eines kurzen Seils ein Gewicht aus Stein oder getrocknetem Ton befestigt ist. Durch Zurückgehen (womit der Gürtel und damit auch die Fäden gespannt wurden) und Herumschwingen der Stange konnte der zweite Arbeiter das Seil fest und gleichmäßig zusammendrehen.

Eine Rekonstruktion[29] dieser Apparatur macht deutlich, daß das Gewicht, das an dem kurzen Seil an der Holzstange angebracht war, dafür sorgte, daß dieses schnell (im und entgegen des Uhrzeigersinns) um die Holzleiste rotieren konnte – je nachdem, welche Richtung die Fadendrehung haben sollte. Um dies zu erreichen, ist ein fester Griff an der Leiste notwendig; mit kleinen, schnellen kreisförmigen Bewegungen der Hand, die eine ständige Bewegung auf den Griff ausüben, werden die beiden Fäden umeinander gedreht. Die kreisende Bewegung am Ende des Seils (das Seil wurde durch die Zentrifugalkraft gespannt) erhöhte den Impuls der Holzstange. Die Leiste und das Gewicht funktionierten wie ein Schwungrad, indem sie den Widerstand der Fäden überwinden, wenn sie stufenweise umeinander gedreht wurden.

Werkzeuge zum Überprüfen von Steinoberflächen

Drei Werkzeuge aus dynastischer Zeit zum Überprüfen von Steinoberflächen sind bereits in einem früheren SOKAR-Artikel behandelt worden:[30] eine A-förmige »*Lotwaage*« (Abb. 14) zum Herstellen genauer horizontaler Oberflächen von Steinblöcken, ein F-förmiges »*Richtlot*« (Abb. 15) zum Überprüfen von vertikalen Oberflächen und ein aus drei Stäben und einem Seil bestehendes Werkzeug zum Bestimmen der Ebenheit einer Steinoberfläche (Abb. 16, 17). Die beiden Holzrahmen benutzen jeweils ein senkrechtes Lot, um die dauerhafte Genauigkeit des Werkzeugs nach seiner Kalibrierung zu gewährleisten.

Um eine rekonstruierte »*Lotwaage*« genau zu justieren, ist es erforderlich, daß beide Enden des Rahmens eine ruhige Wasseroberfläche berühren, während gleichzeitig auf



<< Abb. 15: ***Nachbau eines altägyptischen Werkzeugs zur Prüfung der Vertikalen (»Richtlot«).*** Foto: Jeffrey Stocks

Abb. 16, unten: ***Umzeichnung einer Abbildung aus dem Grab des Rechmire (Theben-West): Handwerker bei der Prüfung der Oberfläche eines Steinquaders.***

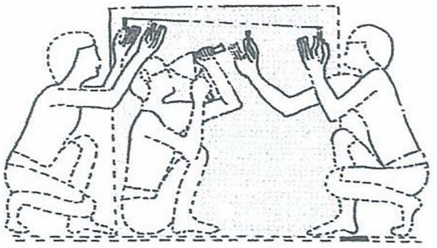


Abb.: Denys Stocks, nach Norman de Garis Davies, Rechmire, Band II, Tafel LXII; bearbeitet: M. Haase

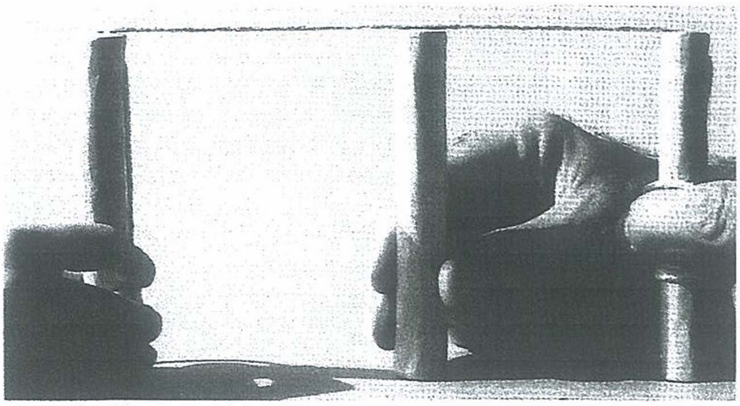


Abb. 17: ***Nachbau eines altägyptischen Meßgerätes zur Bestimmung der Ebenheit von Steinoberflächen. Es besteht aus drei gleich langen Holzstangen, von denen zwei mit einem Seil verbunden sind.*** Foto: Jeffrey Stocks

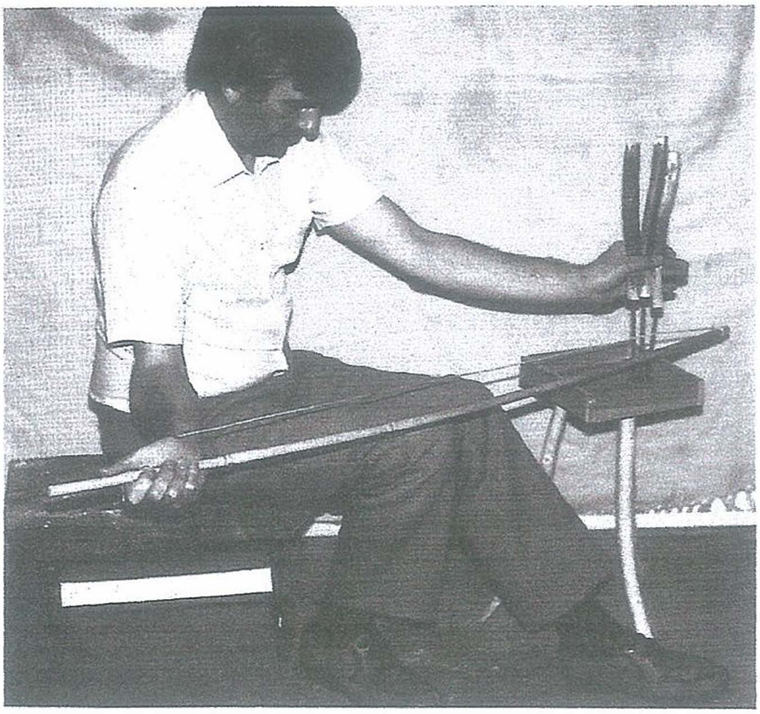


Abb. 18: ***Die Benutzung eines rekonstruierten Werkzeugs zur Bearbeitung mehrerer Steinperlen.*** Foto: Jeffrey Stocks

dem horizontalen Holzteil hinter der senkrechten Lotschnur eine Linie markiert wird. Das rekonstruierte »*Richtlot*« zeigt – vorausgesetzt beide horizontalen Holzleisten haben die gleiche Länge (dabei diente eine Art »*Schiebelehre*« aus zwei Steinen zum Überprüfen der Maße) –, daß dieses Werkzeug ebenfalls sehr zuverlässig war.

Das Werkzeug zur Überprüfung der Ebenheit von Steinoberflächen bestand aus drei Holzstäben gleicher Länge, von denen zwei mit einer Schnur verbunden waren. Indem man den dritten Stab unter das Seil stellte, konnten Unebenheiten auf dem Stein ausgemacht werden. Ein rekonstruierter Satz dieser Stäbe konnte durch die oben bereits erwähnte »*Schiebelehre*« hergestellt werden.

Der Steinbohrmeißel für die Massenproduktion

Nach der Einführung von Kupfer in der prädynastischen Epoche wurden kleine, bogenangetriebene Bohrer aus diesem Material zum Durchbohren von Halbedelsteinen benutzt. Lange, schmale Bohrungen konnten mit dünnen Metallbohrern und einem Schleifmittel leichter hergestellt werden. George A. Reisner fand z. B. mehrere kleine Bronzebohrer in Kerma (Sudan).[31] Zwei dieser Bronzebohrer kamen aus Tumuli, die Reisner in die 2. Zwischenzeit (ca. 1795–1650 v. Chr.) datierte. Zu dieser Zeit erblühte eine einheimische Kultur in Kerma, die ägyptische Techniken verwendete.

Einer dieser Bronzebohrer (5,4 cm lang) ist in einem 2 cm langen taillierten Holzgriff eingepaßt. Eine Rekonstruktion dieses Bohrers wurde aus Bronzeguß mit einem Zinnanteil von 10 % und einem Holzgriff hergestellt.[32] Mit einem kleinen Bogen kann der Bohrer im Uhrzeigersinn und gegen ihn gedreht werden, indem die Schnur um den taillierten Teil des Handgriffes gewickelt wird. Ein rekonstruierter Bohrer, dessen Handgriff einen etwas größeren Durchmesser hat, rotiert mit 1400 Umdrehungen in der Minute. Das Original aus Kerma hätte unter den gleichen Bedingungen 1900 Umdrehungen pro Minute erreicht.

Etwa 200 Jahre später, in der 18. und 19. Dynastie, zeigen Darstellungen in sechs Privatgräbern in Theben-West Handwerker, die gleichzeitig mehrere Bohrmeißel mit einem Bogen antrieben.[33] Jeder Arbeiter durchbohrt auf diese Weise mindestens zwei Steinperlen; aber auch drei, vier oder fünf wurden zur gleichen Zeit durch eine Person bearbeitet. Die Anderung der Einzelbohrtechniken erforderte nicht nur fundamentale Modifikationen an den Bohrern, sondern auch in der Art ihrer Benutzung. Leider hat sich keines dieser Geräte bis zum heutigen Tag erhalten.

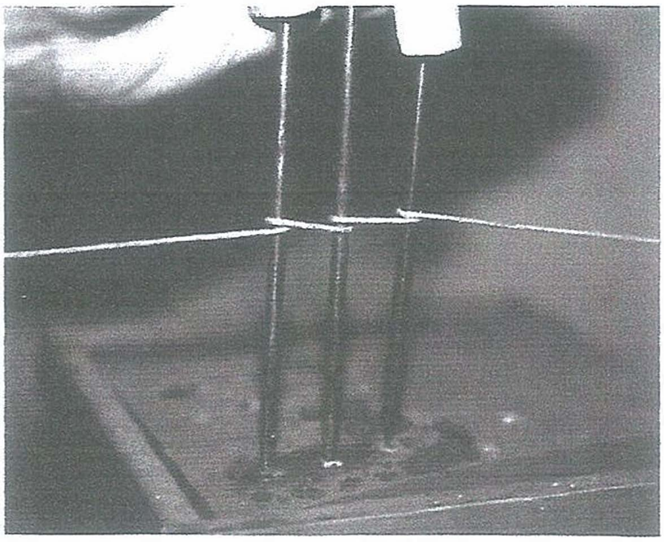


Abb. 19: ***Das Bogenseil bewegt gleichzeitig drei Bronzebohrer.*** Foto: Jeffrey Stocks

Das rekonstruierte Werkzeug[34] zur Bearbeitung mehrerer Steinperlen hat einen kleinen dreibeinigen Tisch, dessen Oberfläche in antiken Zeiten wahrscheinlich mit einer Schicht aus weichem Schlamm gefüllt war, in den gerade Reihen gleichartiger Steinperlen angeordnet wurden. Nachdem der Schlamm getrocknet war, hielt er die Perlen fest in Position. Drei lange Bronzebohrer mit einem Durchmesser von 5 mm rotierten in den Löchern in den unteren Enden von drei Holzgriffen, während die unteren spitzen Enden in die Testperlen bohrten. Das feuchte, flüssige Schleifmittel wurde aus feinem Sandpuder gewonnen, der als Abfallprodukt beim Bohren und Sägen von Stein mit Kupferbohrern und -sägen mit feinem Wüstensand anfällt. Alle drei Bohrer werden in einer Linie in der linken Hand des Handwerkers gehalten (Abb. 18).

Ein langes Seil wird an dem Ende des Bogens befestigt, der am weitesten vom Benutzer entfernt ist. In antiker Zeit gab es am anderen Ende des Bogens eine Schlaufe, die locker am Bogen angebunden war, wo sie die rechte Hand des Arbeiters festhielt. Wird die Schlaufe zur Mitte des Bogens bewegt, lockert sich das Seil und es kann jeweils einmal um die Bohrstäbe gelegt werden (Abb. 19). Wird die Schlaufe nun zum Ende des Bogens bewegt, spannt sich das Seil. Die Tests haben gezeigt, daß die gegensätzlichen Bewegungen des Bogens die Bohrer mit Leichtigkeit drehten.

Der archäologische und experimentelle Beweis legt nahe, daß es zwischen der 2. Zwischenzeit und der 18. Dynastie Erfindungen gab, die einen Bohrer zum Bearbeiten einer Steinperle zu einem Werkzeug für die Massenproduktion umwandelten. Der Mehrfachbohrer ermöglichte es den Handwerkern, ihre Produktionsrate zu erhöhen. Dies führte sicherlich zur Senkung der Kosten für die Schmuckstükke, so daß diese für eine größere Anzahl von Menschen erschwinglich wurden. Diese Bohrtechnik (die Arbeiter werden in den Darstellungen in geordneten Reihen sitzend in kleinen Werkstätten des Neuen Reiches in Theben gezeigt)[35] geht modernen Bohrsystemen zur Massenproduktion um 3500 Jahre voraus.

Gußformen zur Massenproduktion

Methoden zur Massenproduktion fanden auch für den Guß von Metallobjekten und bei der Herstellung von Gegenständen aus Fayence Anwendung. Offene Formen im Sand zum Formen von Metall, die aus prädynastischer Zeit bekannt sind, konnten nur einmal verwendet werden. Petrie fand jedoch wiederverwendbare Formen mit einem feinen Überzug aus Lehm und Asche zum Gießen von Axtköpfen, Meißeln und Messer in der Arbeiterstadt von Kahun (12. Dynastie).[36] Gebrannte Tonformen ermöglichten die Massenproduktion von identisch geformten Werkzeugen, was ihre Verfügbarkeit für die Arbeit erhöhte. Gleichzeitig erlaubten gebrannte Lehmformen (zusätzlich zu Wachs- und Holzformen) die Massenproduktion von Fayence-Gegenständen, die vermutlich aus fein gemahlenem Sandpuder hergestellt wurden, der als Nebenprodukt des Bohrens und Sägens anfiel und daher kleine Kupferpartikel enthielt.[37]

Anmerkungen:

[1] Petrie, Tools, S. 1.

[2] Adams, S. 40, Abb. 21 b.

[3] Adams, Abb. 21 d; Gezahntes Feuersteinmesser, Britisches Museum (Nr. 29288).

[4] Beispiele finden sich im Bristol Museum UK (H1920) und im Britischen Museum (Nr. 29285).

[5] Hoffman, Abb. 49.

[6] Stocks, Experiments, S. 63 f.

[7] Stocks, Experiments, S. 83–96.

[8] Stocks, Experiments, S. 111 f., Abb. 4.3, Tabelle 4.1.

[9] Stocks, Experiments, S. 112 f.; Lucas/Harris. S. 215 f.

[10] Stocks, Experiments, S. 112–136, Tafeln 4.2–4.6.

[11] Z. B. Britisches Museum (Nr. 6040); Davies, Rekhmire, Band II, Tafeln LII und LIII.

[12] Stocks, Experiments, S. 50 f., Abb. 2.42.

[13] Stocks, Experiments, S. 38 f.

[14] Davies, Rekhmire, Band II, Tafeln LII, LIII, Blackman/Apted, Tafel XVI.

[15] Davies, Puyemrê, Band I, Tafeln XXIII und XXV, Davies, Rekhmire, Band II, Tafel LIV, Davies, Two Sculptors, Tafel XI.

[16] Die Rekonstruktionen der Fußgebläse wurden für eine Fernsehproduktion des BBC hergestellt: What the Ancients did for Us – Ancient Egypt. Vorgeführt und gefilmt in Bodiam Castle, West Sussex, Großbritannien, Juli 2004.

[17] Davies, Rekhmire, Band II, Tafel LIII, unteres Register.

[18] Stocks, Experiments, S. 44 f., Abb.n. 2.31–2.33.

[19] Steindorff, Tafel 134; Duell, Band I, Tafel 30; Davies, Gebrâwi, Band I, Tafel XIII; Blackman, Tafel V; Blackman/Apted, Part V, Tafel XVII; Davies, Rekhmire, Band II, Tafel LIV; Davies, Two Sculptors, Tafel XI; Davies, Puyemrê, Band I, Tafel XXIII; Davies, Gebrâwi, Band I, Tafel XXIV.

[20] Stocks, Making stone vessels, S. 596–603, Stocks, Experiments, S. 155–166.

[21] Petrie, Illahun, S. 29, Tafel IX, 6.

[22] Stocks, Experiments, S. 52–55.

[23] Petrie, Kahun, S. 28, Tafeln IX und XVIII, 14; Petrie, Tools, Tafel XLIII, M7.

[24] Carter, Band III, Tafel XXXVIII.

[25] Stocks, Experiments, S. 55, Abb. 2.46.

[26] Blackman/Apted, Tafel XVIII; Petrie, Deshasheh, Tafel XXI.

[27] Stocks, Experiments, S. 67, Abb.n. 2.57–2.60.

[28] Davies, Rekhmire, Band II, Tafel LII.

[29] Stocks, Experiments, S. 51 f.

[30] Stocks, Spuren, S. 5 f. ; Stocks, Experiments, S. 179–200, Abb. 7.2, Abb. 7.3.

[31] Reisner, S. 93 f.

[32] Stocks, Industrial technology, Band 1, S. 216, Band 2, S. 351, Tafel XX, b, XXI, a.

[33] Wreszinski, Band I, Tafel 154; Davies, Puyemrê, Band I, Tafel XXIII; Newberry, Tafeln XVII und XVIII; Wreszinski, Band II, Tafel 313; Davies, Rekhmire, Band II, Tafel LIV; Wreszinski, Band II, Tafel 242; Davies, Two Officials, Band II, Tafel X. The tomb of Sebekhotep at Thebes (Th 63); Wreszinski, Band II, Tafel 360; Davies, Two Sculptors, Tafel XI; Wreszinski, Band I, Tafel 73, a, b.

[34] Stocks, Bead production, S. 2–7; Stocks, Industrial technology, Band I, S. 230–234; Stocks, Ancient factory, S. 526–531; Stocks, Experiments, S. 213–222.

[35] Grab des Sebekhotep in Theben (18. Dynastie). Die Malereien sind im Jahr 1869 von den Wänden des Grabes entfernt worden und befinden sich heute im Britischen Museum in London (Nr. 920).

[36] Petrie, Kahun, S. 29; Petrie, Tools, Tafel LXXVII, W249.

[37] Petrie, Tell el-Amarna, S. 30; Petrie, Arts, S. 118 f.; Lucas/Harris, S. 159; Stocks, Derivation, S. 180.

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Abstract

Over a period of thousands of years, ancient Egyptian craftworkers raised spectacular stone buildings and worked many materials into different types of artefacts. It is clear from an examination of existing ancient tools, from studies of tools illustrated in tombs, but not found by archaeologists, and from marks that can be seen on finished and unfinished objects, that there was a progression in tool design over millennia

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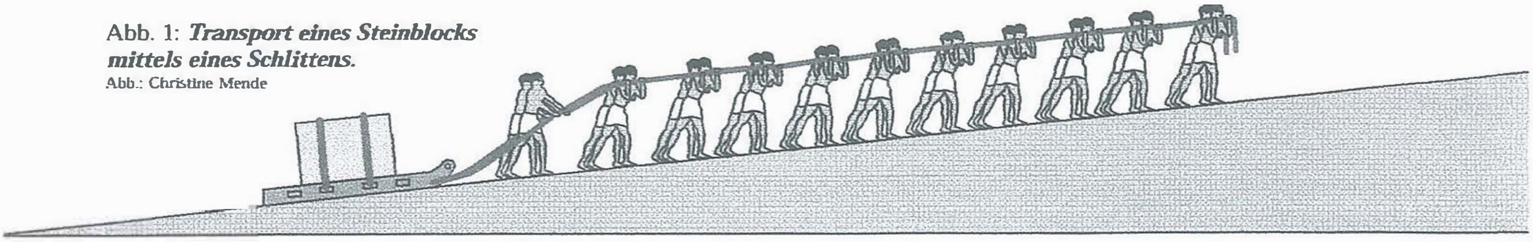


Abb. 1: ***Transport eines Steinblocks mittels eines Schlittens.***
Abb.: Christine Mende

Das Bewegen schwerer Steinobjekte im Alten Ägypten

Experimente in der Ebene und auf geneigten Flächen

Denys Stocks

Beim Bau der Pyramiden, Tempel und anderen großen Bauwerken mußten ägyptische Handwerker Reibung und Schwerkraft überwinden, wenn sie große Steinblöcke in beachtliche Höhen bewegen wollten. In unterschiedlichen Situationen aber konnten die Eigenschaften von Reibung und Schwerkraft bisweilen hilfreich für die Arbeiter sein.

Aus dem Englischen von Christine Mende

Ein wichtiges Hilfsmittel zum Bewegen von Steinblöcken zur Errichtung von Bauwerken war die Transportrampe. In der Zeit des Alten Reiches halfen die Rampen den Arbeitern zum Beispiel beim Bau der Pyramiden in Sakkara und Giza. Im Tempel von Karnak in Oberägypten ist noch heute eine Lehmziegelrampe deutlich erkennbar (Abb. 2).

Hingegen konnte eine Rampe in Form eines absteigenden Korridors auch zum Abwärtsbewegen schwerer Objekten benutzt werden. Ein Beispiel für eine derartige *abwärts* gerichtete Rampe stellt der aufsteigende Korridor in der Cheops-Pyramide auf dem Giza-Plateau dar, der eine Neigung von 26° 2' 30" besitzt.[1]

Neuere Experimente zum Nachweis, wie die Gleittechniken von den altägyptischen Arbeitern angewendet wurden, haben zu interessanten Ergebnissen geführt. Sie deuten klar darauf hin, daß die Winkel der Rampen bei unterschiedlichen Gegebenheiten gezwungenermaßen verändert werden mußten, und daß diese Änderungen ein Standardverfahren beim Transport – aufwärts wie abwärts – von schweren Objekten auf angemessen geneigten Rampen waren.

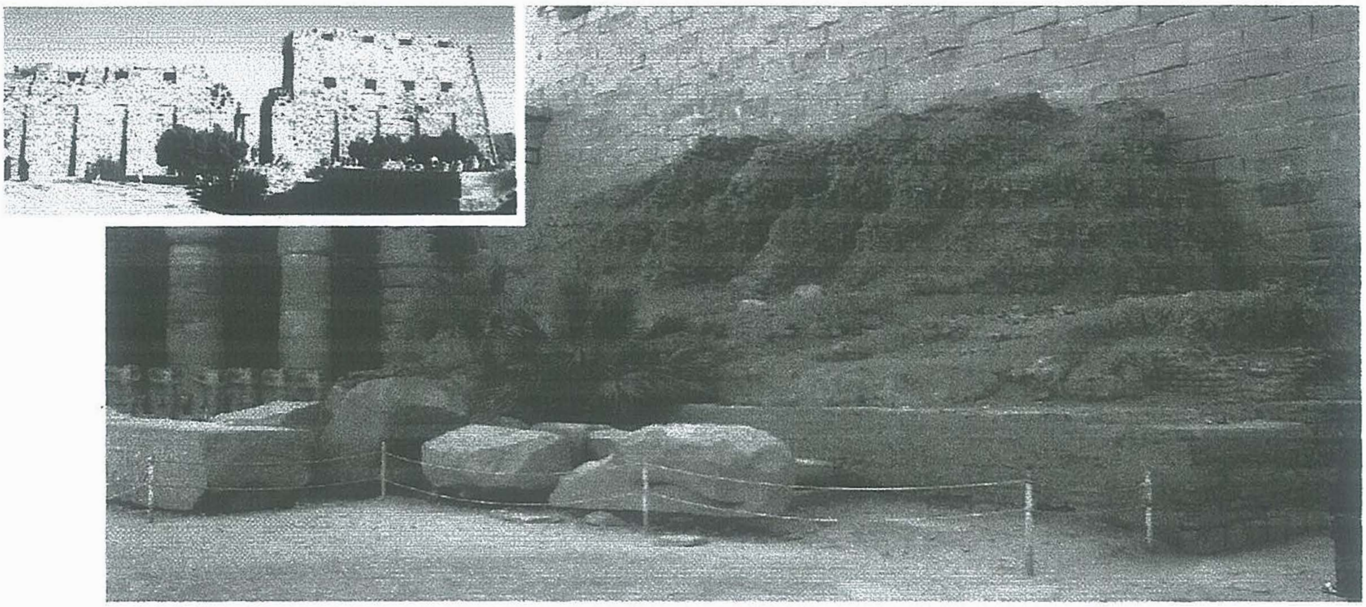


Abb. 2, 3: ***Im Großen Amun-Tempel von Karnak: Reste einer kompakten Ziegelrampe an der östlichen Flanke des über 43 m hohen 1. Pylons aus der 30. Dynastie (kleines Foto: Blick von Westen auf den 1. Pylon).*** Fotos: Michael Haase

Autorenprofil

Denys Stocks (Manchester); Highschool-Lehrer i. R., beschäftigt sich seit 1977 mit der theoretischen und experimentellen Erforschung altägyptischer Handwerkstechniken.

Transporte auf horizontalen und geneigten Oberflächen

Die Reibung zwischen gleitenden Oberflächen großer Steinblöcke stellte beim Bewegen ein schwerwiegendes Problem für die Arbeiter dar: Deren Fähigkeit, die Reibung zu überwinden – hauptsächlich zwischen den Oberflächen zweier horizontal übereinander gleitender Blöcke oder zwischen den Kufen eines beladenen Schlittens und einer horizontalen bzw. geneigten Fläche –, beruhte auf einer pragmatischen Betrachtung des Problems, das durch systematisches Ausprobieren über eine gewisse Zeit letztendlich gelöst wurde.

In wissenschaftlichen Fachbegriffen ausgedrückt, ist die Reibung, die überwunden werden muß, um einen Steinblock in der Ebene zu bewegen, proportional zum Reibungskoeffizienten μ und der Normalkraft N. Der Reibungskoeffizient ist abhängig von der Oberfläche, und die Normalkraft ist die vertikale Kraft der Gravitation, die auf den Block wirkt. Die Kraft F, die aufgewendet werden muß, um einen Block zu bewegen, ist $F = \mu N$.

Wenn F als die Kraft angenommen wird, um die Bewegung zu starten, dann ist μ der Koeffizient der statischen Reibung. Wird F als die ein wenig geringere Kraft angenommen, die nötig ist, um das Gleiten aufrechtzuerhalten, dann ist μ der Koeffizient der kinetischen Reibung. Der Koeffizient der statischen Reibung ist der Tangens des Winkels einer Rampe, bei dem ein Steinblock beginnt abzurutschen. Dies kann experimentell nachgemessen werden. Es läßt sich zeigen, daß die erforderliche Kraft unabhängig von der Kontaktfläche ist und, da das Gewicht konstant ist, die Beweglichkeit des Blockes nur dadurch verändert werden kann, indem man den Reibungskoeffizienten der Oberflächen ändert. Das taten die alten Ägypter, indem sie die Gleitflächen mit einem hohen Grad an Genauigkeit präparierten.

In den 1880er Jahren hat Flinders Petrie die Unebenheiten verbliebender Verkleidungsblöcke auf der Nordseite der Cheops-Pyramide vermessen.[2] Er fand heraus, daß die durchschnittliche Abweichung der Schnittkante eines Steins von einer Geraden und eines rechten Winkels auf einer Länge von 1,90 m nur 0,25 mm betrug.

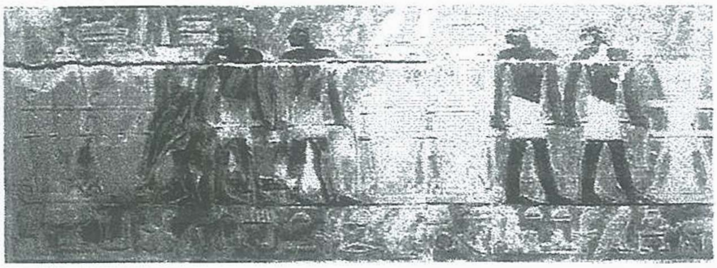


Abb. 4: ***Lastentansporte mittels Schlitten in der Ebene. Darstellung aus dem Grab des Kagemni in Sakkara (6. Dynastie).***

Foto: Michael Haase

In der 4. Dynastie wußten Cheops' Handwerker, daß die Unter- und Oberseiten der Kernmauerwerks- und Verkleidungsblöcke vorbereitet und auf ihre Unebenheiten überprüft werden mußten, um die Stabilität der Pyramide zu gewährleisten. Die Unterseiten der Kalksteinblöcke der Großen Pyramide wurden sorgfältig geglättet, bevor sie im Bauwerk verlegt worden sind.[3] Hingegen wurden die Oberseiten dieser Blöcke erst geglättet und auf ihre Waagerechte überprüft,[4] nachdem man sie in die Pyramide eingefügt hatte. Dies gewährleistete, daß die oberen und unteren Flächen eines jeden Blocks parallel waren, was für jede Lage der Pyramide unerläßlich war. Es gibt eindeutige Hinweise darauf, daß die Ober- und Unterseiten der Blöcke der Cheops-Pyramide mit einer Genauigkeit von 0,25 mm hergestellt wurden.[5]

Die vorbereiteten Blöcke mußten auf einer geschmierten Transportrampe zu dem Ort gebracht werden, an dem sie in der Pyramide, dem Tempel oder einem anderen großen Bauwerk verbaut werden sollten. Zum Transport derartig schwerer Objekte dienten Schlitten.

Die Darstellung eines Schlittens zum Transport eines schweren Steingegenstandes befindet sich im Grab des Djehutihotep (12. Dynastie) in el-Bersheh/Oberägypten.[6] Diese Abbildung zeigt eine etwa 60 t schwere Alabasterstatue des Djehutihotep, die von 172 Männern mittels eines großen Schlittens auf einer ebenen Fläche gezogen wird (Abb. 5). Ein Arbeiter gießt etwas

Abb. 5: ***Umzeichnung einer Darstellung aus dem Grab des Djehutihotep in el-Bersheh (12. Dynastie): ebener Transport einer Monumentalstatue des Grabherrn aus Alabaster.***

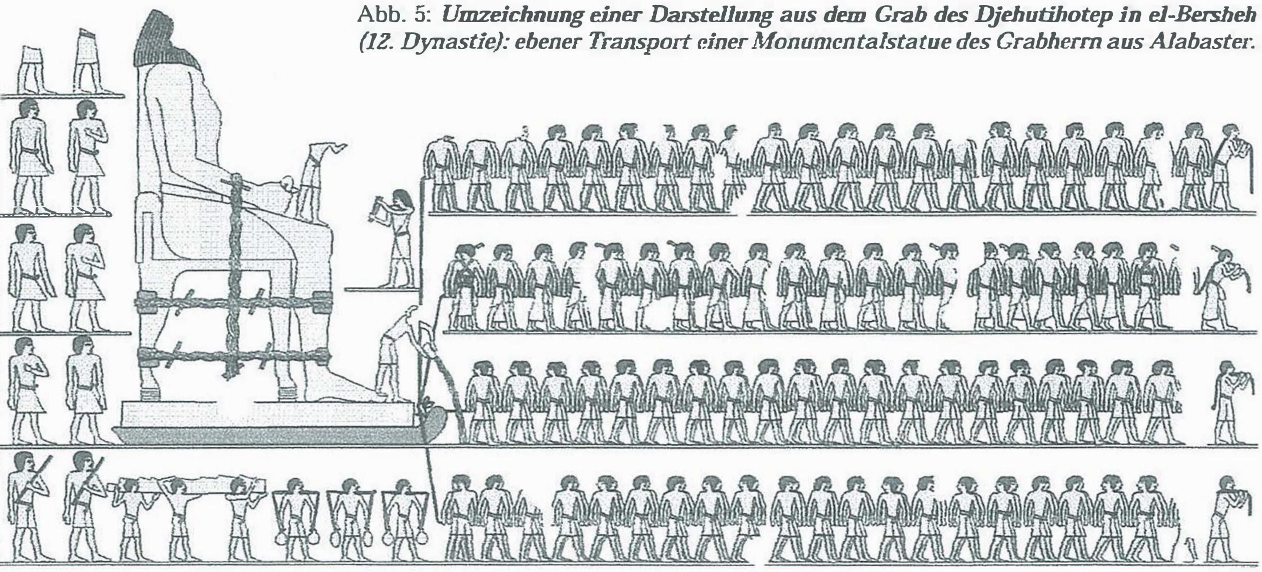


Abb.: Christine Mende, nach P. Newberry, Band I, Tafel XV

Flüssigkeit, vermutlich Wasser, vor die Kufen des Schlittens, um eine schlammige Spur zur Reduzierung der Reibung zu erhalten.

Sobald die Steinblöcke auf dem Bauwerk plaziert waren, benutzten die ägyptischen Steinmetze Gipsmörtel als Gleitmittel,[7] der die Reibung zwischen den Blöcken maßgeblich senken konnte wie auch auf der Unterseite eines Steins und der Oberfläche des Blocks unter ihm. Automatisch und notwendigerweise füllten sich die nicht vollständig passenden horizontalen Fugen mit Mörtel und bewahrten so die Steine davor, zu brechen. Der Mörtel wurde später hart, und die Belastung auf die oberen Seiten der Steinblöcke verteilte sich gleichmäßiger.[8]

Da die beteiligte Oberfläche keine Auswirkung auf die benötigte Kraft hat, sind Experimente mit zwei kleinen Kalksteinblöcken durchgeführt worden (Abb. 6), um die unterschiedlichen Reibungskoeffizienten zu messen. Bei jedem Steinblock wurde eine Seite mit einer Genauigkeit von 0,25 mm vorbereitet.

Im Alten Reich sind die Oberflächen von Kalksteinblöcken mit flachen Kupfermeißeln in Form gebracht worden, die man mit einem Holz- oder Steinhammer vortrieb. Es gibt Beweise dafür, daß zur Bearbeitung von Kalkstein in der 4. Dynastie in Giza auch flache Feuersteinmeißel benutzt wurden.[9] Stumpf gewordene Meißel schärften die Steinmetze mit Feuersteinschabern und schliffen sie mit grobem und feinem Sandstein. Die beiden Kalksteinblöcke des Experiments wurden auf die gleiche Weise vorbereitet. Hartgesteinblöcke sind oftmals vorab mit Steinhämmern und Feuersteinschlegeln bearbeitet worden. Abschließend glättete man die Oberflächen mit Hilfe von grobem und feinem Sandstein. In dieser Phase ist die Ebenheit der Oberflächen der Blöcke normalerweise mit einem speziellen Gerät überprüft worden, so daß anschließend die hochstehenden Bereiche stufenweise mit Schabe- und Schleifwerkzeugen abgearbeitet werden konnten.

Ein derartiges Prüf-Werkzeug bestand aus drei hölzernen Stäben, wobei zwei von ihnen durch eine Schnur verbunden waren, die man bei Gebrauch spannte. Der dritte Stab wurde dann unter die Schnur gehalten und so überprüft, wo sich Unebenheiten auf der Steinoberfläche befinden (Abb. 7).

FLINDERS PETRIE konnte noch eines dieser Werkzeuge – bestehend aus drei Stäben – im Kahun der 12. Dynastie finden.[10] Zwei Stäbe waren an je einem Ende mit einer 2 mm dicken Schnur verbunden. Die Stäbe waren jeweils 12,6 cm lang und variierten in der Länge nur um 0,005 cm. Im Gegensatz zu einer vertikalen Oberfläche hing das Seil bei einer horizontalen Fläche ein wenig durch, so daß die Handwerker eine leicht konkave Oberfläche erhielten.[11] Wie schon PETRIES Messungen der Unebenheiten an etlichen der noch verbliebenen großen Verkleidungsblöcken an der Nordseite der Cheops-Pyramide zeigten, ist es sehr wahrscheinlich, daß dieses Werkzeug bereits in der 4. Dynastie existierte.

Zu Testzwecken wurde ein derartiger Satz Stäbe hergestellt (Abb. 8).[12] Zwei Steine, die fest im Boden verankert waren, dienten zum Abmessen der Stäbe. Diese paßte man genau zwischen die Steine und glich sie damit ab. Durch diese simple Schiebelehre stellte man sicher, daß die Längen der drei Stäbe identisch waren, und dies wiederum garantierte die Genauigkeit des Geräts. Die Präzision des Werkzeugs aus Kahun zeigt, daß

Abb. 6: ***Für die Experimente wurden zwei weiche Kalksteinblöcke benutzt.*** Foto: Denys Stocks

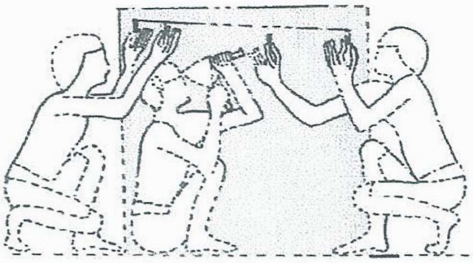


Abb. 7: ***Handwerker bei der Prüfung der Oberfläche eines Steinblocks. Umzeichnung einer Abbildung aus dem Grab des Rechmire (Theben-West).*** Abb.: Denys Stocks, nach N. de Garis, Rechmire, Band II, Tafel LXII; bearbeitet: M. Haase

Abb. 8: ***Nachbau eines altägyptischen Meßgerätes zur Bestimmung von Steinoberflächen.*** Foto: Jeffrey Stocks

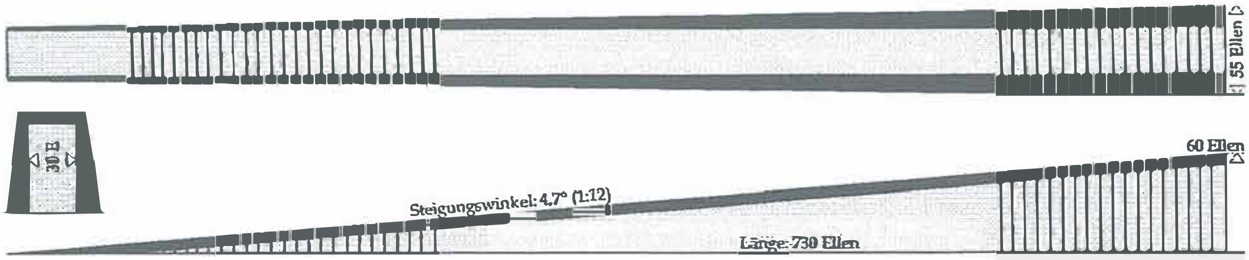


Abb. 9: ***Umzeichnung einer Ziegelrampe (Draufsicht, Querschnitt und Schnitt) nach den Vorgaben aus dem Papyrus Anastasi I nach Ludwig Borchardt. Die Rampe hat eine Länge von etwa 385 m, eine Breite von ca. 29 m und erreichte eine Höhe von ca. 31.50 m.*** Abb.: Christine Mende, nach L. Borchardt, Die Entstehung der Pyramide …, Berlin 1928, S. 223, Abb. 5

die ägyptischen Steinmetze diese einfache Technik beherrschten. Die Längen der nachgebauten Stäbe sind mit einer modernen Schiebelehre überprüft worden und waren ebenfalls bis auf 0,005 cm identisch. Am oberen Ende zweier Hölzer bohrte man Löcher für die Schnur, die beide verbindet. Tests haben gezeigt, daß zugbeanspruchte, 2 mm dicke Seile mit einer Länge von 1,20–2 m um durchschnittlich 0,25 mm durchhängen[13] – vergleichbar mit der Abweichung, die bereits Petrie bei den Verkleidungsblöcken der Cheops-Pyramide gemessen hatte.

Ergebnisse der Gleitversuche

Die beiden vorbereiteten Kalksteinblöcke wurden mit trockenen Oberflächen aufeinandergesetzt und der untere Block so weit geneigt, bis der obere Stein anfing, sich zu bewegen.[14] Der Neigungswinkel betrug in diesem Moment 36°. Der Tangens dieses Winkel ergab einen Reibungskoeffizienten von 0,73.

Dieser Test wurde anschließend mit nassem Mörtel wiederholt, den man auf die Oberseite des unteren Blokkes auftrug. Der obere Steinblock begann sich nun bereits bei einem Winkel von 8° zu bewegen, was einem Reibungskoeffizienten von 0,14 entspricht.

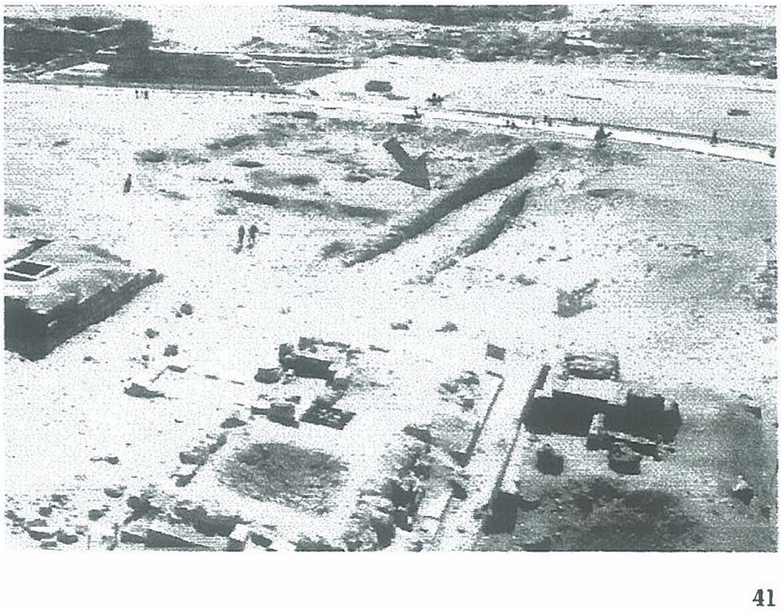
Ein weiteres Experiment zeigte, daß eine hölzerne Schlittenkufe auf nassem Lehm zu einem vergleichbaren Koeffizienten führte.

Flinders Petrie gibt an, daß ein Verkleidungsblock an der Nordseite der Cheops-Pyramide »*etwa 16 Tonnen*« wog (16300 kg).[15] Zur Bestimmung der Kraft F, um einen derartigen Block auf einer ebenen und geglätteten Fläche zu bewegen, muß sein Gewicht zuerst in die Normalkraft N (Newton) konvertiert werden, d. h. 16300 × 9,8 = 159745 N (die Normalkraft von einem Kilogramm beim Zusammenpressen von zwei Flächen entspricht 9,8 N auf Meereshöhe). Die Gleitkraft F kann nun durch Multiplizieren des Reibungskoeffizienten 0,73 mit der Normalkraft N berechnet werden: 0,73 × 159745 N = 116610 N.

Um die Kraft zu bestimmen, den gleichen Block auf einer mit nassem Mörtel geschmierten Fläche zum Gleiten zu bringen, wird der geringere Reibungskoeffizient 0,14 benutzt: F = 22363 N. Dieses Ergebnise zeigt, daß fünfmal weniger Kraft vonnöten ist als bei trockener Fläche. Dieser Reduktionsfaktor gilt für alle Steinblöcke – und zwar unabhängig von ihrem Gewicht und der Oberfläche, auf der sie aufliegen.

Die Darstellung im Grab des Djehutihotep (Abb. 5) weist darauf hin, daß ein Arbeiter in der Lage war, eine Zugkraft von 500 N (etwa 50 kg) aufzubringen, um die Statue in Bewegung zu versetzen. Folglich konnten 45 Arbeiter einen geschmierten Steinblock von 16300 kg Gewicht auf einer ebenen Fläche in Bewegung setzen. Einmal zum Laufen gebracht, verringerte sich der Kraftaufwand, womit der Block mit einer konstanten Geschwindigkeit weitergezogen werden konnte.

Abb. 10 >: ***Blick von der Pyramide G Ic nach Südosten. Der Pfeil markiert die Reste einer Rampe, die vermutlich für die Errichtung dieser Königinnenpyramide verwendet wurde*** (Abb. 11, oben). Fotos: Michael Haase



Ein kleiner, geschmierter Kernmauerwerks- oder Verkleidungsblock der Cheops-Pyramide mit einem Gewicht von etwa 2750 kg würde eine Anfangskraft von 3770 N (ungefähr 385 kg) erfordern. Um einen derartig schweren Steinblock auf einer ebenen, geschmierten Fläche in Bewegung zu versetzen, wären also acht Arbeiter notwendig.

Das Ziehen eines Steinblocks mittels eines Schlittens auf einer Schrägen, wie es zum Bau der Pyramiden notwendig war, erforderte ein Gleichgewicht zwischen der benötigen Kraft und dem Winkel, der ein Abrutschen bedingt hätte. Der Kraftaufwand, um einen Block auf einer Steigung zu ziehen, ist doppelt so groß wie auf einer Ebene.[16] Dies und das Risiko, daß der Block während des Ziehens abrutscht, bedeuten, daß die Rampe einen geringeren Steigungswinkel haben muß. Dies erklärt, warum der Steigungswinkel einiger antiker Rampen kleiner als 8° war – dem *»Abrutsch-Winkel«* für einen lehmgeschmierten Schlitten.

Eine Darstellung eines Steigungswinkels mit weniger als 8° findet sich auf einem Papyrus aus der 19. Dynastie im Britischen Museum in London.[17] Es zeigt einige Maße für eine hypothetische Rampe (Abb. 9). Ein Schreiber namens Hori fragt einen weiteren Schreiber Amenemope, wie viele Ziegel nötig sind, um eine Rampe von 730 Ellen (383,25 m) Länge, 55 Ellen (28,90 m) Breite und einer Höhe von 60 Ellen (31,50 m) zu bauen. Berechnungen zeigen, daß die Rampe ein Steigungsverhältnis von 1:12 hat, was einem Neigungswinkel von fast 5° entspricht.

Die Steigung der Rampe im unvollendeten Totentempel des Mykerinos (4. Dynastie) beträgt 1:8 bzw. mehr als 7°.[18] Der Aufweg zwischen dem Taltempel des Chephren und seiner Pyramide hat eine Steigung von 6° (Abb. 13, 14). Im südlichen Teil des Gebietes des Gebel el-Asr in Unternubien,[19] in dem sich Gneiss-Steinbrüche befinden, wurden zwei Transportrampen aus Stein gefunden. Beide haben eine Länge von ungefähr 9 m und an der Stirnseite eine Höhe von 1,20 m, d. h. ebenfalls eine Steigung von 7°.

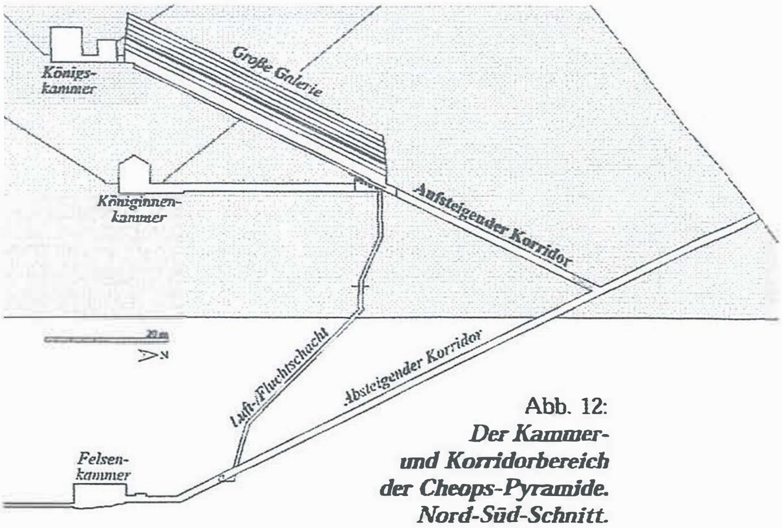


Abb. 12: ***Der Kammer- und Korridorbereich der Cheops-Pyramide. Nord-Süd-Schnitt.***
Abb.: Michael Haase

Zwei Beispiele für noch steilere Rampen stellen der aufsteigende Korridor in der Cheops-Pyramide mit einem Steigungswinkel von 26° 2' 30" (ein ansteigender innerer Korridor ist ebenfalls eine Rampe), in dem drei Granitblockiersteine herabgelassen wurden (Abb. 12), und der 49 m lange absteigende Korridor in der Pyramide von Cheops' Sohn Djedefre in Abu Roasch dar, der eine Neigung von 22° 35' hat und in die Grabkammer der Pyramide führt (Abb. 15).

Abb. 13, 14: ***Am Aufweg der Pyramide des Chephren.*** Unten: ***Blick den Aufweg auf Höhe des Sphinx entlang in Richtung der Chephren-Pyramide (im Hintergrund).*** Rechts: ***Der Sphinx, sein vorgelagerter Tempel und Chephrens Grabmal im Hintergrund. Der Pfeil markiert den Aufweg.***
Fotos: Michael Haase

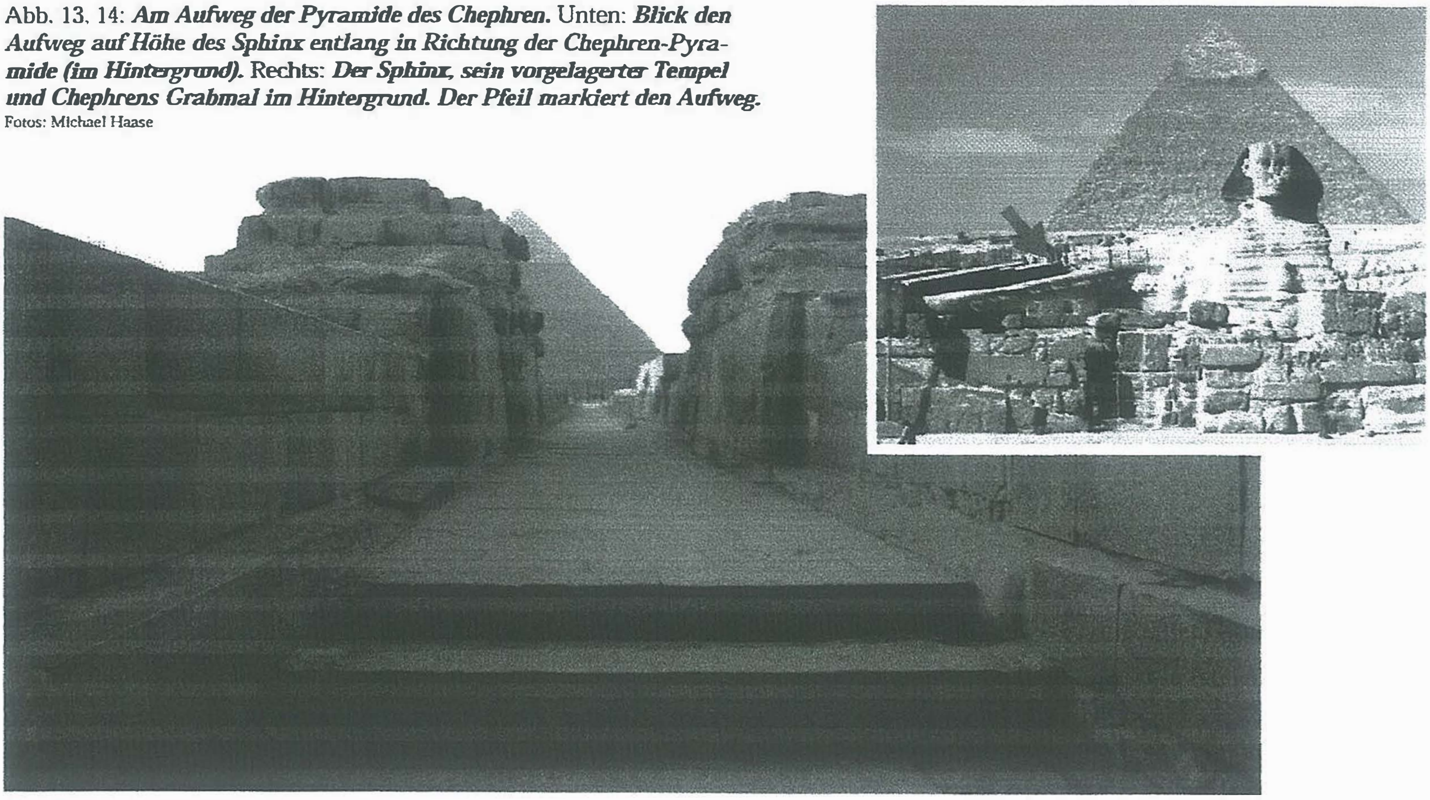


Abb. 15: ***Die Überreste des absteigenden Korridors in der Pyramide des Djedefre bei Abu Roasch.*** Foto: Michael Haase

Zusammenfassung

Die Experimente ließen erkennen, daß es wesentliche Vorteile gab, Steinblöcke und beladene Schlitten auf mörtel- und lehmgeschmierten ebenen Flächen zu bewegen, und sie legten einen Steigungswinkel von 7° für eine geschmierte Transportrampe nahe. Dieses Ergebnis wird durch die Winkel existierender antiker Rampen gestützt. 16 Arbeiter konnten ohne weiteres einen 2750 kg schweren Verkleidungsblock der Cheops-Pyramide über eine derartige Rampe ziehen (doppelt so viele Arbeiter wie zum Ziehen eines Blockes auf einer geschmierten ebenen Fläche).

Die Test haben klar und deutlich gezeigt, daß die alten Ägypter schwere Objekte über steilere Rampen herabgelassen haben, die im trockenen Zustand eine akzeptable Reibung für diese Aufgabe hatten. Rampen mit einer Neigung von 8° (und mehr) wurden wahrscheinlich im trockenen Zustand benutzt, da es sowohl kontraproduktiv als auch gefährlich gewesen wäre, eine derartige Rampe zu schmieren: Ein beladener Schlitten wäre unkontrolliert herabgerutscht.

Die beiden erwähnten Rampenbeispiele (aufsteigender Korridor der Cheops-Pyramide und absteigender Gang der Djedefre-Pyramide) waren nicht stark genug geneigt, um trockene Steinblöcke ohne zusätzlichen Kraftaufwand der Arbeiter herabgleiten zu lassen. Jedoch unterstützte die Gravitation, die auf den Block wirkte, die Arbeiter in einem erheblichen Maß.

Diese Technik erlaubte einen relativ geringen Kraftaufwand, um die Reibung zwischen einem Steinblock oder einem Schlitten und der trockenen Oberfläche der Rampe zu überwinden, sogar bei einer Rampe die (mindestens 10°) weniger als 36° Neigung hat, dem Winkel, bei dem ein Steinblock auf einer trockenen Rampenoberfläche aufgrund der Gravitation unkontrollierbar herabrutschen würde. Dies gab den Arbeitern einen angemessenen Sicherheitsspielraum, um Objekte eine trockene Rampe mit einer größeren Neigung als 8° herabgleiten zu lassen, genau wie bei einer geschmierten Rampe mit einer geringeren Neigung als 8°. Die Erkenntnis, daß eine trockene, steile Rampe eine höhere Reibung zwischen Steinblock und Rampenoberfläche besitzt, zeigt, daß diese Art der Rampe (zum Herablassen von Steinblöcken) viel kürzer gebaut werden konnte als die notwendigerweise viel längere, weniger geneigte, geschmierte Transportrampe, die zum Hochhieven von Steinblöcken auf ein Bauwerk gebraucht wird.

Anmerkungen:

[1] Edwards, S. 111.
[2] Petrie, Pyramids, S. 44; Petrie, Building.
[3] Edwards, S. 284.
[4] Clarke/Engelbach, S. 100.
[5] Stocks, Spuren, S. 6.
[6] Newberry, I, Tafel XV.
[7] Edwards, S. 284.
[8] Clarke/Engelbach, S. 78–80.
[9] Jenkins, S. 81, Tafel 55.
[10] Petrie, Kahun, S. 27, Tafel IX, 13.
[11] Stocks, Experiments, S. 191; Stocks, Immutable, S. 575.
[12] Stocks, Immutable, S. 575, Abb. 3; Stocks, Experiments, S. 188 f.
[13] Stocks, Experiments, S. 190.
[14] Stocks, Experiments, S. 196, Abb. 7.18.
[15] Petrie, Pyramids, S. 44.
[16] Timoshenko/Young, S. 162–167.
[17] Papyrus Anastasi I (BM 10247).
[18] Edwards, S. 280.
[19] Siehe Shaw et al.

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ABSTRACT

Gypsum mortar lubricated sliding experiments between flat contact surfaces of two stone blocks reveal significant advantages in moving stone artefacts along mortar- and mud-lubricated horizontal surfaces, and suggest a safe transport ramp upwardly inclined at an angle of not more than 7°. A dry sliding experiment indicates that stone artefacts could safely be lowered down dry, steeper ramps without causing danger to workers.

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Stoneworking, Pharaonic Egypt

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How *did* Pharaonic stoneworkers shape and hollow stone vessels and sarcophagi, fashion and fit stone blocks into pyramids and temples, cut granite obelisks and incise deep hieroglyphs into them, create stone statuary, and drill the hardest semi-precious stones in Egypt?

In the Nagada I Period (ca. 4000–3600 BCE; *see* NAQADA (NAGADA)), vessels made of basalt, granite, calcite (Egyptian alabaster), gypsum, and limestone were produced in increasing numbers (Baumgartel 1955: 102–19). During this period, stoneworkers hollowed lug-handled basalt jars with grinding stones and sand abrasive at el-Amra, UPPER EGYPT.

The Nagada II Period (ca. 3600–3200) saw the introduction of truly smelted and cast copper tools (Amer 1933, 1936). These included small chisels, adzes, axes, saws, and knives (*see* COPPER: METALLURGY, PHARAONIC EGYPT). The casting of copper into Pharaonic reusable pottery moulds (Petrie 1890), which replaced earlier, single-use sand moulds, significantly shortened tool manufacturing times.

Recent experiments made with hardened replica copper and bronze chisels, necessarily hammered cold as in ancient times, revealed that they only effectively cut gypsum, soft limestone, red sandstone, and steatite without being seriously damaged (Stocks 2003: 56–69). Even calcite causes unacceptable damage to edged copper tools. Experimental iron chisels additionally cut hard sandstone.

The Pharaonic stoneworker quarried and carved low and incised hieroglyphs and reliefs into soft limestone (Figure 1) and red sandstone by utilizing mallet-driven copper and bronze chisels, or by using a copper adze for skimming thin shavings off soft limestone, particularly for dressing tomb walls at Thebes (Mackay 1921: 163–4), afterward smoothing surfaces with flint scrapers and sandstone rubbers.

Figure 1 Two low-relief hieroglyphs in limestone being cut with a replica copper chisel. © Denys A. Stocks.

Comprehensive tests with different types of stone tools reveal that only flint chisels and punches can cut small pieces out of basalt, diorite, granite, porphyry, quartzite, and similar hard stones (Engelbach 1923: 40; Stocks 2003: 83–95). The particularly deep hieroglyphs in rose granite obelisks and temple columns were achieved simply by continually hacking bits out of the stone. All hard stone artifacts, like vessels, could be brought to shape by this technique. Rough and smooth sandstone rubbers, finely ground sand, and probably mud finished some hard stone surfaces as smooth as glass (Stocks 2003: 91).

The quarrying and rough shaping of hard stone for certain artifacts, such as statuary, needed stone hammers, picks, mauls, and axes, but dolerite balls pounded out trenches around obelisks in order to detach them from the rose granite at Aswan (*see* ASWAN AND HINTERLAND). Heavy statues were roughly shaped at the quarry, reducing their weight for transportation to other sites for final finishing operations (*see* TECHNOLOGY, EGYPTIAN).

Before the availability of cast copper, stoneworkers probably employed a short length of the hollow common reed as a tubular drill, rotating it on necessarily dry

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sand abrasive with a bow for removing the interiors of vessels manufactured from hard limestone and calcite. This technique considerably shortens the time needed to hollow out vessels by breaking off the core left in its tubular-shaped slot. Experiments show that reed tubes could effectively have drilled slate, calcite, and hard limestone before ca. 3600 BCE, particularly for perforating mace-heads made from these three stones (Stocks 2003: 12–13).

It is likely that the common reed served as the pattern for fabricating Nagada II copper drill-tubes, which were able to drill into igneous stones. Confirmation is provided by examples of Pharaonic tubular-shaped holes in stone containing finely ground sand, tinged green by copper carbonate. The use of bronze tubes is proved by a 19th Dynasty tubular drill-hole in a granite jamb, which has bronze particles in it (Metropolitan Museum of Art catalogue no. 13.183.2).

Test drilling indicates that a bow-driven tubular drill *gyrates*, causing the hole, and the core created inside the tube, to taper, in a fashion similar to tapering holes seen in Predynastic hard stone vessels. These holes possess fine striations on their walls: drilling experimental holes with sand demonstrates that striations are similar in roughness, depth, and width to ancient striations (Stocks 1986).

A stoneworker's perception of *dry* desert sand was that it flowed like a fluid, just like very wet sand. But the experimental drilling of hard stones with wet and then dry desert sand shows that the cutting rates are similar. Waste dry sand powder, still containing copper particles worn off the drill-tube, is easy to remove; it sticks together inside the tube, and periodically can be withdrawn from the hole. Experimentally firing the powders mixed with alkali and water made body and glaze ceramic materials, similar to ancient FAIENCE (Stocks 1997). Other experiments demonstrate that the experimental powders make an abrasive for polishing stone and for drilling hard stone beads with pointed copper and bronze drills (Stocks 1989, 2003: 216–20).

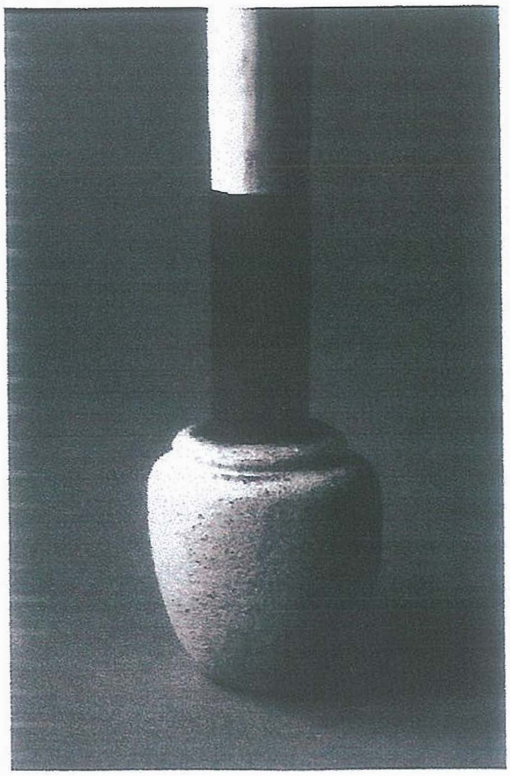

Figure 2 Drilling a test limestone vessel with a reconstructed copper tube fitted to the stone vessel drilling tool. © Denys A. Stocks.

The manufacture of stone vessels needed a combined stone-weighted drilling and boring tool (Davies 1943: 2, pl. LIV; Blackman and Apted 1953: 5, pl. XVII). Reconstructed tools worked by continuously twisting and reverse-twisting the drill-shaft (Stocks 1993). The non-gyratory motion produces parallel holes and cores, without applying sideways forces to already shaped vessels (Stocks 2003: 108). No complete stone vessel drilling/boring tools have ever been located in Egypt, but they are depicted as hieroglyphs and in tomb representations dating from the 3rd to the 26th Dynasty.

There is evidence that vessels were sometimes drilled with tubes of increasing diameter on the same axis to weaken a core (Figure 2). For some vessels, though, several small-diameter touching holes were drilled around the mouth. The stone vessel-making tool can also bore out bulbous vessels. After carefully breaking out the drill-core(s), a bulbous vessel would be bored by using figure-of-eight-shaped stone borers of different lengths to suit the changing internal diameter. Such borers, also using sand as the abrasive, would be driven in a horizontal position with a forked wooden stick securely roped to the main tool's shaft, without having to remove the copper drill-tube. Conical stone borers formed a vessel's mouth, and flint crescent-shaped borers, not used with sand, hollowed soft gypsum vessels (Stocks 1993, 2003).

Making an experimental stone vessel with a reconstructed tool wore down the fork holding the borer. In ancient times, a worker needed only to exchange the old forked shaft for a new one; the more expensive main tool was not damaged. Replacement of expendable forked shafts, worn-out copper drill-tubes, and stone borers made the stone vessel-hollowing tool the first one known to have interchangeable parts (Stocks 1993, 2003: 139–68).

Pharaonic stoneworkers used large-diameter copper drill-tubes for hollowing royal stone sarcophagi and the lifting holes in some lids. Marks made by tubular drills can be seen in the calcite sarcophagus of the 3rd Dynasty pharaoh SEKHEMKHET, and in Khufu's (*see* KHUFU (CHEOPS/KHEOPS)) 4th Dynasty granite sarcophagus, the first to be hollowed from an igneous stone with copper tubes. Copper tubular drills were also used for other purposes, such as for delineating eye, ear, and nose parts in statuary.

Using Sir Flinders Petrie's measurements of a curved mark left in the east internal wall of Khufu's sarcophagus, metric calculations show that an 11 cm-diameter tube was used to drill it (Petrie 1883: 86; Stocks 2003: 173). This diameter translates closely to the ancient system of measurement of six royal finger-widths (one and a half royal palms), where 28 finger-widths made a royal cubit – equal to 52.3 cm in length (*see* WEIGHTS AND MEASURES, PHARAONIC EGYPT).

The internal length and width of Khufu's sarcophagus were decided simply by centralizing the nearest whole number of the drill-tube's diameter, eighteen along the length and six along the width, when just touching each other, leaving an adequate amount of stone after drilling around the perimeter to form the side and the end walls (Stocks 2003; 2005). After drilling weakening holes in the isolated central mass, all cores could be broken off. Several drilling levels were needed to hollow the sarcophagus. The interior surfaces were dressed with flint chisels and punches.

An experiment in a granite quarry at Aswan, Upper Egypt, using a reconstructed 8 cm diameter copper drill-tube, required three workers to operate it – one at each end of the long driving bow, and one holding the large capstone in which the drill-shaft rotated. Drilling the granite to a depth of 6 cm required sustained effort over a period of 20 hours of drilling. The core was removed from the tubular-shaped hole by soundly hammering a tapered chisel vertically between the tapered wall of the hole and the tapered core, putting it under great tension below the chisel. The core suddenly cracked off at its base (Stocks 2001).

The earliest sawing marks on a stone sarcophagus also date to the 3rd Dynasty, as evidenced by chevron-shaped saw marks on Sekhemkhet's calcite sarcophagus. The chevron was created by cutting the stone from both sides of the block at an angle; this technique allowed a shorter saw to be used. However, Khufu's granite sarcophagus was sawn to shape horizontally with a saw somewhat longer than the length of a side, allowing for the saw's to and fro movements. The finding of Pharaonic saw-slots and sawing marks on hard stone building blocks, sarcophagi, and statuary, together with associated copper-contaminated, finely ground quartz sand, indicate that a flat-edged copper saw, using desert sand abrasive, was employed for sawing calcite and all harder stones. However, tests confirm that a serrated copper saw cuts soft limestone, which ancient masons exploited (Stocks 2003: 67).

The characteristic cross-sectional V-shaped marks in ancient saw-cuts in hard stone have been replicated in granite with a reconstructed flat-edged copper saw at Aswan, weighted at each end with stones. Two workers were needed to drive the 1.8 m long, 6 mm thick blade to and fro upon dry sand abrasive. Due to its weight and length, the saw rocked from side to side during each forward and backward movement, wearing away the slot's walls and making it V-shaped in cross-section, similar to a V-shaped slot seen in Hordjedef's unfinished 4th Dynasty granite sarcophagus in the Cairo Museum (CM JE54938), and a similar slot in a basalt pavement block at the Great Pyramid, GIZA (Petrie 1883: 174–5; Stocks 2001).

The introduction of sawn and drilled hard stone sarcophagi spectacularly increased Egypt's consumption of copper. Calculations based upon extensive granite sawing and drilling tests revealed a loss of nearly 450 kg of copper ground from the tools used to saw and drill Khufu's sarcophagus, turning about 40 tonnes of sand into copper-contaminated powder, and taking approximately two years to complete. The sawing and drilling experiments suggest that ancient stoneworkers eventually became ill with silicosis from inhaling very fine, micron-sized stone dust (Stocks 2003: 176, 237–8).

The fitting of large numbers of stone blocks together commenced with DJOSER's 3rd Dynasty Step Pyramid at SAQQARA. This building consists of relatively small, soft limestone core- and casing-blocks. The end-faces of two adjoining blocks only fitted closely together for a few centimeters, most of the joint being filled with gypsum mortar and limestone chippings. However, Khufu's masons closely fitted the whole area of two large adjacent limestone casing-blocks' end-faces together (*see* BUILDING MATERIALS AND TECHNIQUES, PHARAONIC EGYPT).

The key to flattening a stone block's surface accurately is the ability to test, and therefore to direct, the surface to flatness. The stoneworker's surface testing tool consisted of a set of three short wooden rods, all matched in length, with two of the rods joined by a taut string exiting a hole drilled into the top of each rod. The earliest set, found at 12th Dynasty Kahun (EL-LAHUN) by Petrie (Manchester Museum catalogue no. 28), are accurate in length to each other within two to three thousandths of an inch (0.05 mm), an accuracy easily achievable with an outside caliper made from two stones embedded in the ground (Petrie 1890; Stocks 2003: 188). In use, the taut string enabled the third rod to test the stone's level beneath it.

Experiments with a replica set of rods and string demonstrated that a surface area equal to the end-face of one of the adjoining casing-blocks, fitted into the base row of the northern face of the Great Pyramid, could be worked to an accuracy of 0.25 mm, as measured by Petrie in the early 1880s (Petrie 1883: 44; Stocks 2003).

Ancient surface testing rods determined whether a granite obelisk's top surface was level along its full length, while still in its horizontal quarry position. Over this distance, even when tightly tensioned, the string curves slightly toward the stone. Naturally, the masons carved the surface to follow the string's catenary curve, making it slightly concave. A rose granite obelisk from the Luxor Temple, now in Paris, has this anomaly (Gorringe 1885).

Two known tools for testing horizontal and vertical in stone blocks are a water-calibrated A-shaped wooden frame and an F-shaped wooden frame, both fitted with a hanging plumb line (Clarke and Engelbach 1930; Stocks 2003: 179–200). Other important building tools consist of the wooden set square, lever, cubit measure, sledge, measuring cords, and leveling lines.

Recent sliding tests by Stocks (2003: 195–6) reveal that *five times* less force was needed to slide limestone blocks over each other when lubricated with liquid gypsum mortar than dry blocks: Great Pyramid blocks were moved in a similar manner. Experiments also demonstrate that a ramp's muddy surface, inclined upward at 8° or more, allowed a block-laden sledge to begin sliding back down it: unlubricated ramps or shafts, sloping at higher angles, were mostly used safely to lower blocks down them (Stocks 2009: 38–43). Significantly, some extant ancient ramps, inclined at 7° or less, completely eliminated the risk of a lubricated loaded sledge sliding dangerously out of control.

The making of jewelry in Egypt utilized semi-precious stones (*see* JEWELRY, PHARAONIC EGYPT). Beads of carnelian and amethyst were first roughly formed by shaping the pieces with flint tools, followed by grinding on harsh and smoother grades of sandstone. A runny, finely ground abrasive polished the beads.

The earliest material in use for perforating stone beads was flint, but long, narrow perforations can only be achieved with metal drills, and Pharaonic ones of copper and bronze were used, again in conjunction with a fine abrasive paste. A bead-drill, force-fitted into a waisted wooden handle, could be rotated with the string of a small bow. However, in the 18th and 19th Dynasties (ca. 1550–1186 BCE), six tomb representations at Thebes show single bead drillers each simultaneously revolving several bronze drill-rods with a long bow (Davies 1923: 2, pl. X; 1943: 2, pl. LIV).

Operating reconstructed drilling equipment demonstrated that a 10 mm diameter amethyst bead could be perforated with a single 1 mm diameter drill in five hours (Stocks 1989). However, using three drills simultaneously perforated three beads in a similar time, dramatically increasing the production rate for stone beads. Artwork from the tomb of Sebekhotep depicts two rows of drillers, each worker drilling three or four stone beads simultaneously (British Museum catalogue no. 920). This illustration reveals a workshop employing mass-production principles in the New Kingdom at Thebes.

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10

SOME EXPERIMENTS IN ANCIENT EGYPTIAN STONE TECHNOLOGY

Denys A. Stocks

Introduction

Two classes of highly visual and numerous stone artefacts known from ancient Egypt are stone beads incorporated in jewellery products, and stone vessels. Experimental archaeology can be used to explore the manufacturing techniques for both.

Ancient Egyptian craftworking representations, dated to the Old, Middle, New Kingdom and Late Periods, illustrate workers using tools for hollowing stone vessels. Unfortunately, none of the tools depicted in the illustrations have been located by archaeologists, except for some stone and flint borers that can be associated with the representations. Whilst considerable information can be gleaned from the illustrations, much uncertainty regarding the tools' construction and operation prevents a fuller understanding of these tools and their uses.

Six New Kingdom tombs at Thebes each show a representation indicating the existence of an important and systematic drilling procedure for making the threading holes in hard stone beads. In these scenes, single craftworkers simultaneously rotate between two and five bronze drills with one bow, each drill perforating a stone bead beneath it. No parts of the represented tools have ever been found – the bow, the bronze drills, the wooden shafts in which the drills rotate and the three-legged table at which the craftworker sits, which contains the beads being drilled.

In trying to establish the tools and techniques developed by ancient workers for making stone vessels, and beads, several factors need to be examined: the archaeological and pictorial evidence for tools; the ancient Egyptian environmental factors influencing the designs of tools, whether known or indicated by good evidence, for example the employment of desert sand with stonecutting drill-tubes and borers, the drill-tubes thought to be based on nature's hollow reed; the natural resources available to craftworkers; the tool marks seen upon stone vessels and upon stone beads, and also the marks found upon identified tool parts, such as the specially carved stone borers and the flint crescent-shaped tools for boring soft stone.

Experimental preparations carried out by the author

After gathering all the available archaeological and pictorial evidence for artefacts, tools and working procedures, there followed the establishment of a home workshop, including facilities to melt and to cast copper and bronze, and to manufacture tools and artefacts constructed from a variety of man-made and naturally occurring materials. In all, over 200 experimental replica and reconstructed ancient Egyptian tools made of stone, copper, bronze, iron, wood, and other materials, received detailed analysis and testing. Evaluation of the tools' test performances upon various materials included comparisons of marks made on those materials by the research tools to marks seen on ancient artefacts: similarly, marks on the research tools were compared with marks on ancient tools.

In order fully to examine the functions of replica and reconstructed stone vessel tools, two experimental vessels were shaped and hollowed with them. Similarly, the experimental use of a replica single bead drill, predating the Theban tomb depictions of New Kingdom multiple drills, allowed comparisons to be made with the operation of reconstructed multiple bead drilling tools. It is clear that a number of skills, for example, scraping, grinding, casting, hammering, sawing, chiselling, cutting and polishing, were the forerunners of similar methods used by engineering craftworkers today. Here, I present my research into two ancient crafts, demonstrating the original replica and reconstructed tools made over 30 years ago.

1. Stone vessel manufacturing

Predynastic and Dynastic stone vessel preparations

The technology for hollowing stone vessels became fully established in the Predynastic period. At first, hard stone vessels were laboriously hollowed with hand-held stone borers, used in conjunction with desert sand abrasive: softer stones, like gypsum and soft limestone, could be bored with 1/4 to 3/4 crescent-shaped flint tools, without the need of sand abrasive. Experiments with reed tubular drills, necessarily rotating on dry sand abrasive, suggest that these tools could have been utilised for drilling the stone vessels made from calcite, in addition to the hard limestone vessels, before the introduction of copper tubes in the Nagada II period (ca. 3600–3200 BC). Copper tubes could drill very hard stones, again using sand abrasive. In this period, hard stone vessel types included the oblate spheroid supplied with two perforated tubular-shaped lugs, for example, Manchester Museum 1776, made of syenite. Taller, bulbous, lugged jars from the Predynastic period are made of porphyry, diorite, breccia, serpentine, calcite and limestone. The industry continued to flourish in Early Dynastic times, but softer stone vessels predominated, such as those made from calcite. Although some stone vessels are cylindrically shaped, and only require a tubular drill for hollowing, many vessels are bulbous. An excellent example is a limestone/breccia double-handled jar from the Nagada II period in the Metropolitan Museum of Art (12.183.2). Bulbous vessels required widening below the shoulder, using boring processes that were quite separate from the tubular drilling of the interior.

Copper, sand and flint – three key tool materials

It is generally thought that the cold beating, or forging, of truly smelted and cast copper into tools and other artefacts first occurred in Egypt ca. 3600 BC,[1] castings being made in rudimentary open moulds at this period.[2] It is believed that copper tubes were indispensable tools for drilling hard stone such as granite.

In Egypt, copper tubular drills – no examples have been located – were presumably used for the initial hollowing of the interiors of vases and jars.[3] Striations are clearly visible on the inside *vertical* walls of vessels, caused by the sand abrasive employed with the drills.[4] Subsequently, bulbous vessels – those considerably wider internally than at the mouth – were further hollowed by grinding with another tool, a stone borer of elongated form. The mid-point of its long axis narrowed equally from both sides. Seen from above, the borer assumes the shape of a figure-of-eight, enabling a forked shaft to engage with the waist. The top is normally flat, the bottom curved. This particular borer type has been discovered at Hierakonpolis, a site associated with Late Predynastic and Early Dynastic stone vessel production.[5] A previously made tubular hole, after core extraction, could be enlarged with successively longer figure-of-eight borers to achieve the correct internal form.

The striations seen upon stone vessels, and on the bottom surfaces of stone borers, are generally about 0.25 mm wide and deep, actuated by quartz crystals in sand abrasive. This material has been connected to stone borers by N. de G. Davies, J. E. Quibell and F. W. Green. Davies pointed out that the cutting edge was horizontal and the surface near it was scored by parallel grooves, suggesting that sand was the real excavating medium.[6] The undersides of figure-of-eight shaped borers found by Quibell and Green[7] at Hierakonpolis have also been scored at both ends by parallel striations. These striations describe an arc, centred upon each borer's vertical turning axis.

All of the tomb representations show that stone vessels were always carved to shape *before* the drilling and boring commenced, and this procedure was followed in making the experimental vessels. The author's experimental working of hard stone indicated that the *exterior* shaping of all hard stone vessels, including those manufactured of basalt, diorite, porphyry, breccia, granite, and even the softer calcite, in every period, must have been completed with flint chisels, punches and scrapers.

The incisions and the other marks obtained with the experimental flint chisels, punches and scrapers on the calcite and the igneous stones matched the marks on a variety of ancient stone artefacts manufactured from similar stones. Even soft limestone and gypsum vessels, which could have been shaped with copper tools, probably needed awkward places shaping with flint scrapers; necks, rims and the undercutting of vessels' shoulders all required skilled carving techniques using exceptionally sharp tools. The differing hardness of stones is important for the experimental project. It is presumed that flint and chert were used to carve hard stones because the material is hard, sharp and readily available. The following table gives the Mohs scale of hardness for stones mentioned in this paper:

Stone	*Mohs scale of hardness*
agate	6.5
amethyst	7
basalt	7
breccia	5–6
calcite	3–4
carnelian	7
chert	7
diorite	7
flint	7
garnet	6.5
granite	7
gypsum	2
hard limestone	6
hard sandstone	5
porphyry	7
quartz	7
quartzite	6–7
serpentine	4
soft limestone	2.5
steatite	3

Table 1. List of stones and Mohs hardness numbers

Pictorial evidence for stone vessel making

Neither the forked wooden shafts, nor the tools that drove them, have been discovered in Egypt. However, the tool is depicted as a hieroglyph, the first known one occurring in the Third Dynasty at Saqqara.[8] During the Old Kingdom, this hieroglyph is used as an ideogram in words for 'craft', 'art', and other related words. It is shown as a *forked central shaft* with two stone weights, or bags of sand, fastened underneath an inclined, curved, tapering handle.[9] This fork engages with a stone borer (*Fig.* 1), its depiction in side elevation concealing its figure-of-eight, or circular, shape. The forked shaft ideogram shows only the visually interesting and informative view of the fork and borer, rather than the ambiguous view of a tube, which would appear to be part of the shaft; this follows ancient Egyptian artistic protocol. The weights placed a load upon a tool's cutting surface. There is no depiction of the means of traction, either by a bow or by hand rotation.

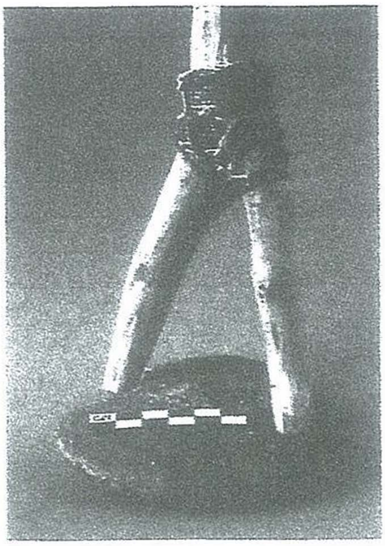

Figure 1. A reconstructed elongated stone borer engaged with a forked shaft.

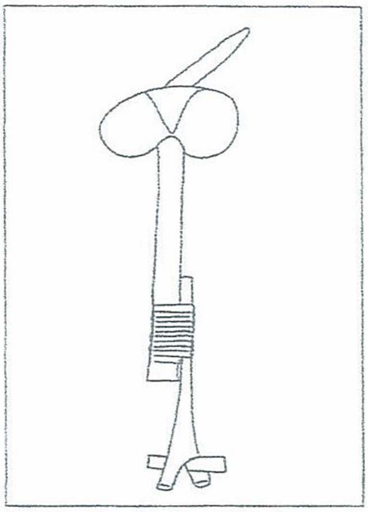

Figure 2. A Twelfth Dynasty representation depicting a forked shaft fastened to a central shaft. Drawing by Denys A. Stocks from Fitzwilliam Museum E55.1914. (Courtesy of the Fitzwilliam Museum.)

Different forms of the stone vessel-making tool are illustrated in a number of Egyptian tombs constructed between the Fifth and the Twenty-sixth Dynasty. In these illustrations, craftworkers grip the tools with their hands, the vessel obscuring the lower, working end of the tool's shaft. However, sometimes a second shaft is shown lashed to the central shaft by a thin rope. This method can be seen in a painted Twelfth Dynasty tomb representation in the Fitzwilliam Museum, Cambridge E55.1914, a limestone fragment from Lahun (*Fig.* 2).

By the Middle Kingdom, the double-stone method of weighting the tool is shown alongside a single, perforated hemispherical stone weight, in which the central shaft is located.[10] In New Kingdom times, the ideogram representing the tool changed to a forked shaft lashed to a central shaft, with one hemispherical stone weight.[11] In a Twenty-sixth Dynasty tomb representation[12] two weights are again in evidence, and this reflects the Twenty-sixth Dynasty's interest in the Old Kingdom period. Also, separate hanging weights are much easier to manufacture and fit than a centrally drilled hemispherical weight but make it less easy to use the tool.

Analysis of the pictorial evidence

The evidence of the hieroglyphs and the tomb representations clearly shows that the drilling tool was in use at least from the Third to the Twenty-sixth Dynasty. The central drill-shaft is round, having been manufactured from a suitable tree branch. The tapered and angled top part, or handle, of the central shaft seems to correspond to the angle and shape of a branch which grows from a larger stem, this stem acting as the central shaft. The main stem is cut away just above the branching stem and smoothed. The forked shaft, made from a branch by equally shortening the two stems forming the fork, is inverted before lashing it to the tool's central shaft.

The tomb evidence shows a clear progression from the Old Kingdom drill, weighted with two stones or sandbags, to the Middle Kingdom period, where drills with two weights are used alongside drills with a single, hemispherical stone. The single weight may have been exclusively in use during the New Kingdom period, but in the Twenty-sixth Dynasty two weights are adopted. It is obvious that the drill needed to be weighted and balanced, but it is also clear that the weights are situated near to the top of the tool to allow for deep penetration into a vessel.

Present tests, by the author, on tools reconstructed from materials in use by ancient craftworkers, demonstrate that a continuous rotary action, where the tool's handle is used as a crank, causes the drill to wobble alarmingly, making it difficult for a human to perform and, indeed, to control. The stone weights fly outwards and increase the wobbling. Such use of the tool must cause serious damage to any vessel, not to mention the extreme tapering of the cores and the hole when in use with a tubular drill (the inside of the tube, rubbing on sand abrasive, causes severe wear to the top of the core). This is at variance with the archaeological evidence for parallel-sided cores and holes in ancient vessels. An example of this is a small, unfinished and uncatalogued Old Kingdom calcite vase in the Petrie Collection. A tube about 8 mm in diameter, with a 1 mm-thick wall, was drilled down 7.5 cm into the vase, leaving the unbroken parallel-sided core within its parallel-sided hole. A bow, therefore, was not used for driving this drill-tube. The use of bow-driven tubes for *most* stone vessel manufacture must firmly be rejected. However, the *tapered* holes in lugs carved on some hard stone vessels were drilled from each end with bow-driven tubular drills acting on sand abrasive, e.g. Manchester Museum 1776. Tapered holes having striations within them indicate bow-driven tubular drills.

The experiments clearly demonstrate that the tool's weights place a load on the tubular drills, stone borers, or crescentic flint or chert borers, and that the craftworker repetitively twists the tool clockwise, and then anticlockwise, to its starting position. With tubular drills, no other action produces parallel-sided cores.

The pictorial, archaeological and experimental evidence, therefore, confirms that this ancient implement was in use as a *combined* drilling and boring tool, a reasonable assumption being that the tool for the preliminary drilling operations must have been fitted with a copper tube and, later in dynastic times, a bronze tube force-fitted to the bottom of its central shaft (*Fig.* 3). After drilling, a forked shaft is lashed to the central shaft, probably still fitted with its tubular drill, in order to drive stone borers. The tool has been named the Twist/Reverse Twist Drill (TRTD), calling it a 'drill', even though its other function is for boring.

Another type of Egyptian stone borer – an inverted truncated cone with two slots cut opposite each other in its upper, horizontal surface – was employed to shape a vessel's mouth; there is an uncatalogued cone borer with similar cut-outs in the Petrie Collection. As previously mentioned, crescent-shaped flint and chert tools, also engaged by forked shafts, could only be used for cutting soft stones, such as gypsum, without sand abrasive. In extended use, the forks of the reconstructed tools show wear.[13] A worn forked shaft could be replaced simply by lashing a new one to the central shaft, much as a drill-bit is changed in a modern electric drill. As the destruction of a *forked central* shaft would have rendered the whole tool useless, it may have evolved from this original configuration. A central shaft, fitted with a tube and weight, probably lasted for many years.

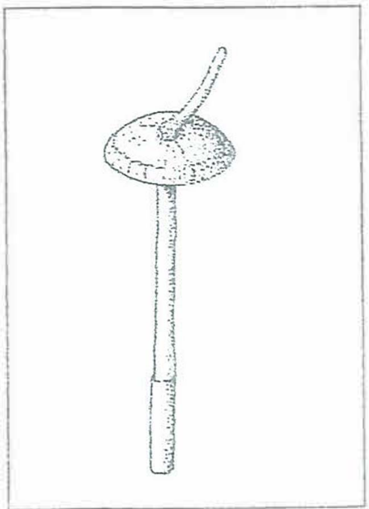

Figure 3. A proposed drilling version of the tool for making stone vessels, which has a copper tube force-fitted to its central shaft. Drawing by Denys A. Stocks.

Some tomb illustrations may display a central shaft fitted with a tube, which is being used to drill adjacent holes around the perimeter of wide-mouthed vessels to remove the central mass (hand-operated sandstone grinders finished the final shape).[14] There is strong evidence that tubes were used either to drill single, or to drill multiple numbers of adjacent holes in stone vessels. For example, eight tubular-shaped marks, left after the cores had been removed, are visible in an unfinished porphyry vase in the Cairo Museum (JE18758).

It is likely that the drilling tool did not change in form, except for the manner in which it was weighted; a tubular drill would not have damaged its wooden shaft during use, and a succession of new tubes could be fitted to the same shaft time and time again.

Making reconstructed tools

Experimental reconstructed TRTDs were manufactured by the author from suitable tree branches, after seasoning. The bark was first removed with a flint knife or scraper, each branch being adapted by cutting away the central stem above the place where it forks; the remaining part is sawn to length and carved into a taper. In all, ten experimental TRTDs were fitted with nearly pure copper or bronze tubular drills, these being fabricated from rolled sheet, or cast in vertical, tubular-shaped moulds. All of these tools were weighted with two stones, except for a 3 cm-diameter TRTD shaft, which was fitted with a single stone weight (after the Eighteenth Dynasty tomb representations). The weight was drilled through its vertical axis with a tube fitted to another TRTD, the finished weight being adjusted to be a force-fit on the drill-shaft, just under the inclined handle.

Three TRTDs were fitted with lashed-on forked shafts; they drove a flint crescent and two figure-of-eight shaped stone borers, these borers being chipped to shape out of oval pebbles. The smaller stone weights, for the smaller TRTDs, were hung in coarse nets knitted from string. The largest TRTD's stone weights, each weighing 3 kg, were secured with ropes positioned into grooves ground into the stones.

Tubular holes produced by *bow-driven* tubes in large, *hard* stone artefacts, such as sarcophagi, were nearly circular in shape, but the difficulties of making stone vessels with thin walls exclude this technique. The mechanical stresses imposed upon the thin stone walls by gyratory forces in bow-drilling break the vessel. Also, the to and fro movement of a bow causes sand trapped outside the tube to enlarge the hole out towards the external wall of the vessel, particularly in softer stones; ancient vessels were always shaped in advance of the drilling and boring operations and, clearly, hole elongation would have meant the failure of each vessel.

The tests revealed that it is best to twist the tool by hand, first clockwise, by approximately 90°, and then anticlockwise to its starting position. One hand grips the inclined and tapered handle; the other hand grips the central shaft, just below the weights. The curved handle fits the semi-clenched hand perfectly, and must have been chosen and carved for this purpose. Once the hands are comfortably gripping the handle and the shaft, they are not moved from that position, except for rest or to renew the sand abrasive. This comment applies *only* to the tubular drills and the circular stone borers which, even when partially rotated, cut out the stone around the whole of their circumferences. In using figure-of-eight and crescentic stone borers, the craftworker must periodically change the position of the hands on the tool *after* a full clockwise or anticlockwise twist, in order to grind out the stone evenly around the whole circumference of a vessel.

Sir Leonard Woolley suggested that Mesopotamian figure-of-eight shaped stone borers, similar to ones found in ancient Egypt, were rotated with a bow.[15] However, test boring by this method showed that the figure-of-eight borer immediately jammed in a prepared hole, mainly caused by a massive amount of friction between the borer and the sand abrasive. It is likely that this was exacerbated by an out-of-balance centrifugal force acting upon one end of the borer as the bow-rope began to twist the forked shaft, forcing the tool into the wall of the hole. Additionally, the bow-rope slipped on the shaft. The experiments do not support the driving of Egyptian or Mesopotamian figure-of-eight stone borers with a bow-driven forked shaft.

Demonstrating stone vessel reconstructed tools

Experimental vessels were carved to shape from rough blocks of soft limestone with large and small copper adzes, flat and crosscut copper chisels, a mallet, flint chisels, punches and scrapers and sandstone rubbers. No set measurements were adhered to, the shapes of the vessels being achieved by acting upon intuitive judgements. The shoulders of one of the vessels, a barrel-shaped vase, were wider than its flat bottom; it made sense to align the narrower base surface directly under the centre of the projected top surface, and ensure parallelism between them. The top and the bottom surfaces were finished before any further shaping takes place.

The initial shaping of the curved sides for both vessels now commenced. Copper adzes were utilized to pare away the limestone from the top to the bottom. However, a hand-held, adze-shaped flint blade could also have been employed for this operation: if this vessel had been manufactured from granite or porphyry, stone hammer-driven flint chisels and punches would have been used to chip away the stone, as copper would have been too soft. During this shaping, constant checking of the relationship

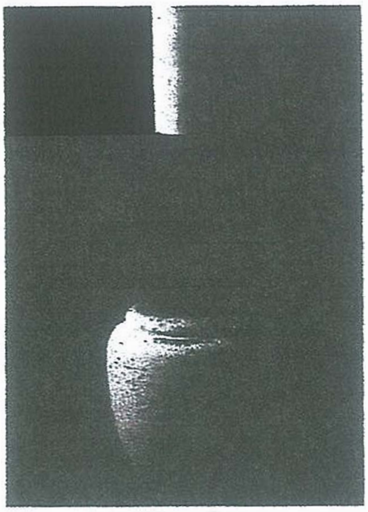

Figure 4. Drilling the vase with a 4 cm-diameter copper tube.

between the top and the bottom surfaces to the curved sides became necessary.

The second phase of the shaping could now begin. Using small copper chisels, a mallet, and flint scrapers of different shapes and sizes, allowed the shoulders and neck gradually to be carved into shape. After checking the final form of the barrel-shaped vase, sandstone rubbers of graded textures were used to smooth the whole of its surface. The final smoothing, however, was deferred until the completion of the hollowing. The vase measured 10 cm in diameter, 10.7 cm in height, with a neck diameter and height of 7.5 cm and 1 cm respectively (*Fig.* 4). The other vessel's exterior and interior remained unfinished.

The vase's first stage of hollowing commenced with a 4 cm-diameter tubular drill, initially penetrating part-way into it. It was decided to tubular-drill the vase using sand abrasive, even though soft limestone was probably hollowed with crescent borers in ancient times. This method appears to be the safest way for an apprentice to practise the hollowing tasks. An unprovenanced and uncatalogued calcite vessel in the Petrie Collection has a circular groove upon its top surface; some red paint is still visible on the groove. The groove is likely to have been made in order to locate a tubular drill, which prevented the tube from 'wandering' around the surface when first rotated. The experimental vase was similarly prepared. Firstly, the drill-tube's end surface was coated with red paint (probably red ochre in ancient times), and pressed flat after correctly positioning it, so that a mark can be made defining its circumference. This allowed a groove to be chipped out with a flint chisel and mallet along the circular mark. In fact, two grooves are so prepared, one within the other, in order that two different diameter tubes could be used for the drilling.

There is evidence that several different diameter tubular drills, rotated upon the same axis, could be utilized on single artefacts in ancient times. In the Petrie Collection is an uncatalogued tubular-shaped basalt core; horizontal striations are in evidence on its internal and external surfaces. The core's date and provenance are unknown. The core does not taper at all; its internal and external sides are perfectly parallel. Flinders Petrie ventured an opinion that the core came from an enlarged hole in basalt; a lesser hole had been cut and found too small, and then a larger hole was made, detaching a tube of basalt.[16] A different interpretation may be presented to explain its shape. Possibly, the lesser hole, after the removal of the solid core left by the smaller tubular drill, was deliberately enlarged, reducing the risk of breaking a vessel by trying to remove one larger, solid core.

The use of this technology in the experimental vase showed that the tubular-shaped core breaks upon removal; soft stone is liable to fracture easily. But hard stone, such as basalt, may occasionally have survived removal intact. Both ends of the Petrie Collection basalt tube are flat. One might have expected the tube to possess a jagged end, where it was broken out from the hole. Nevertheless, there are solid cores in the Petrie Collection which have flattened and polished ends,[17] although the purpose for this is unclear.

The experimental vase was then drilled to a depth of 3.5 cm with the 4 cm- and the 2.2 cm-diameter tubular drills. The cores were carefully removed with a mallet and a copper chisel. Pieces of the solid core were removed first, followed by the tubular core (*Fig.* 5). The soft mallet blows are directed toward the centre of the vase. Other experimental work with the smaller tubular drills upon some sandstone and limestone specimens showed that the twist/reverse twist forces, exerted upon a slim stone core by the finely ground sand powder trapped between the core and the drill's interior wall, caused it to fracture at its base. Care was taken to eliminate any lateral forces acting upon the core during these tests. The twist/reverse twist driven tube can also, very carefully, be forced to one side to snap off a slim core. The only other alternative is with a wedge. However, although this technique was employed for the drilling of sarcophagi, a wedge utilized to snap off a core in a vessel could break out its wall.

The second limestone vessel was hollowed out by the tubular drilling of adjacent, touching holes around a stone vessel's perimeter, with a central hole to weaken the central mass. It is evident that this method is very useful in reducing risk of breakage, but inevitably takes longer because performing a greater number of operations.

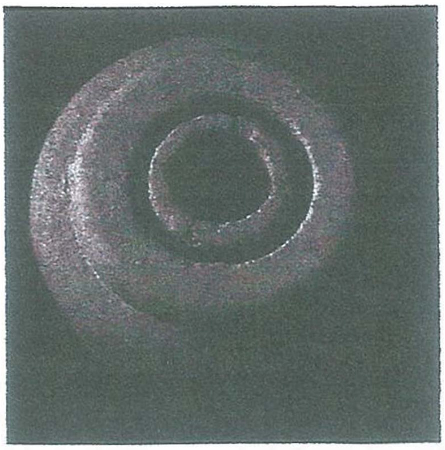

Figure 5. The removal of the small solid core precedes the breaking of the tubular stone core.

The first vase now required undercutting at the shoulders, and then hollowing to follow its external shape. There are several ways that this might have been achieved in ancient times. Firstly, one might tubular-drill the vase completely to the bottom and then bore out the remainder of the stone with figure-of-eight shaped stone borers. Alternatively, one might tubular-drill the vase to a point just below the shoulders, then use *only* successively larger figure-of-eight borers until the bottom is reached: however, this method is not supported by the striations seen on extant figure-of-eight borers, which are under the borers' extremities, not under their central parts.

The experimental method involved tubular-drilling the vase to a point below the shoulder and introducing a first figure-of-eight shaped borer to force a sideways cut: this was assisted by initially scraping a shallow groove with a flint tool. The limestone vase was filled with dry sand abrasive up to the level of the top of the borer, and a forked shaft engaged with it. Gradual twist and reverse twist actions, together with a new grip every few twists, allowed the stone borer to settle into a fully horizontal position (*Fig.* 6). The scraped groove was further cut sideways and downwards by these actions. The dry sand abrasive slowly erodes the vase interior, and also the borer. Occasionally, the ground down sand powder was poured out of the vase, and fresh, coarse sand admitted. Each successively longer figure-of-eight borer further increased the undercutting to a point where the central hole needed deepening by tubular drilling, followed by core removal and figure-of-eight boring until the final depth was reached. After boring, a series of raised ridges, or cusps, were created as each successive borer ground away a groove into the vase's wall. These were smoothed away by long, hand-held sandstone rubbers, the bottom being smoothed with a rounded stone borer, in use with sand abrasive.

Figure 6. The stone borer settling into a fully horizontal position within the stone vessel.

Results

The table below summarises the cutting ratios and rates for a number of stones:

Stone type	*Ratios of metal: stone wear rates*			*Cutting rates (cm^3/hour)*	
	by volume		*by weight*	*copper tube*	*bronze tube*
	copper tools	*bronze tools*	*copper and bronze tools*		
rose granite	1 : 3	1 : 3	1 : 0.9	0.3	0.3
diorite	1 : 3	1 : 3	1 : 0.9	0.4	0.4
hard sandstone	1 : 20	1 : 23	1 : 7	1.8	2.0
hard limestone	1 : >100	1 : >100	1 : 8	3.0	2.9
calcite	1 : >100	1 : >100	1 : 12	6.0	6.0
soft limestone	1 : >400	1 : >400	1 : >50	6.0	6.0

Note: the specific gravity of copper = 8.94 g/cm^3, approximately 3.3 times the stones' specific gravities. The rate of drilling these stones with a twist/reverse twisted drill-tube is 5 times slower than with a bow-driven drill-tube.

Table 2. Copper and bronze twist/reverse twist drill-tubes' cutting ratios and rates – average of all experiments.

The total time for manufacture, 22½ hours, is equal to about three, eight-hour working days for the barrel-shaped limestone vase, but igneous stone vessels would have required much more time to complete. For example, tests indicate that the author's tubular drilling of granite takes about 15 times longer than the tubular drilling of soft limestone.

2. Developments in stone bead drilling techniques

Beaded materials and shapes

In the Predynastic period, beads were made from copper, gold, silver, greenish-blue glazed quartz and steatite, glazed faience cores, and stones; these included agate, calcite, carnelian, diorite, garnet, limestone and serpentine.[18] The Egyptians' most favoured bead shapes comprised rings, barrels, cylinders, convex bicones and spheroids, but amulets and pendants were also threaded into strings.

Ethnographic parallels, archaeological and iconographic evidence suggest that hard stone beads were first formed by breaking up pebbles, then roughly shaping the pieces by chipping with flint tools, followed by grinding on harsh and smoother grades of sandstone. Final polishing was

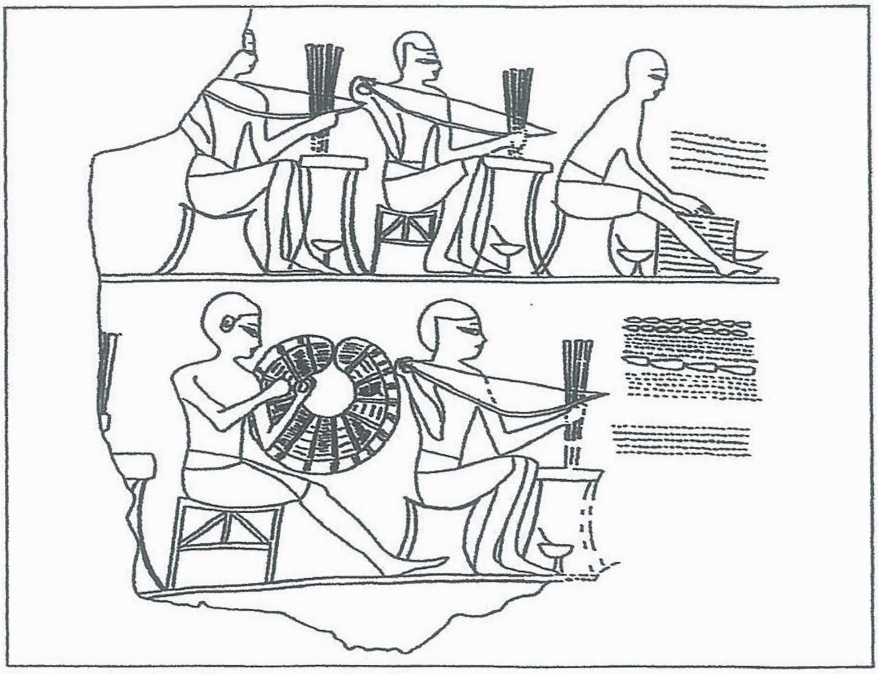

Figure 7. A New Kingdom bead making workshop at Thebes, Upper Egypt. Two drillers rotate four drill-rods each and one driller turns three drill-rods. A fourth driller is shown on the left of the scene. From the tomb of Sebekhotep at Thebes. Drawing by Denys A. Stocks from BM 920. (© Trustees of the British Museum.)

achieved by rubbing along grooves carved into a wooden or stone bench, which sloped away from the polisher, the grooves being filled with a runny, finely-ground polishing abrasive; this polishing technique is displayed in the Eighteenth Dynasty tomb of Sebekhotep at Thebes (*Fig.* 7).[19]

Threading perforations in stone beads required drilling with tools which changed in form and materials over thousands of years. The earliest material for drilling stone beads was flint, but eventually copper and bronze drills employed a fine abrasive material for making small diameter perforations.

Single-bead drilling tools

After the introduction of copper in the Predynastic period, small, bow-driven drills for bead perforation were probably made of this metal, although Dynastic flint micro-drill bits associated with beads are known from several sites, including Early Dynastic Hierakonpolis, Old Kingdom to First Intermediate Period Elephantine and even New Kingdom Amarna. At Hierakonpolis such drill bits were found in connection with other bead-

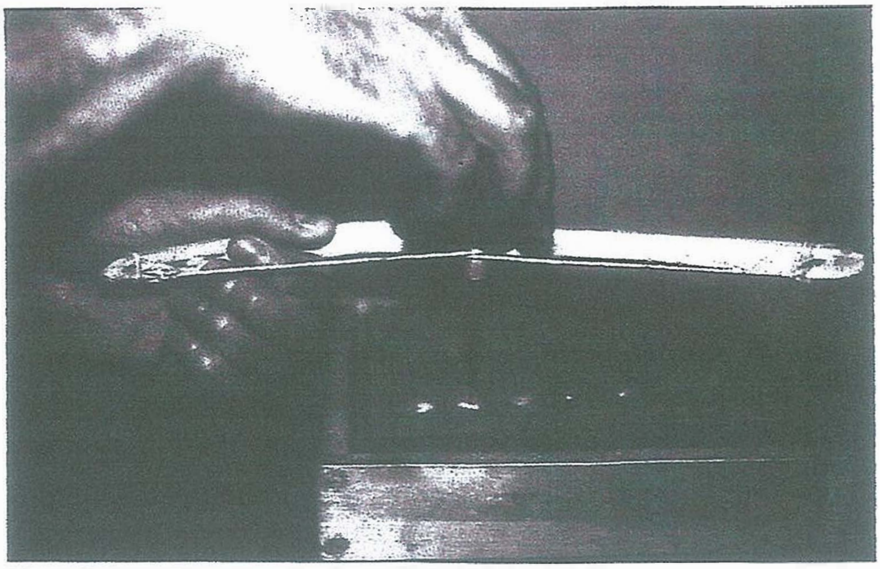

Figure 8. A small bow rotating the replica single bead drill.

making material including partially made beads. However, long, narrow perforations are much easier to make with metal drills and an abrasive paste, than with flint micro-drills. G. A. Reisner[20] found several bronze bead drills at Kerma in the Sudan. Some drills date to ca. 1970–1935 BC, but two drills fitted with wooden handles, excavated by Reisner from tumuli, date to the Second Intermediate Period (ca. 1795–1650 BC); at this time, a native culture employing Egyptian techniques flourished at Kerma.

One of the bronze drills force-fitted into a waisted wooden handle engages with a bow-string. Reisner measured the length of drill, without the handle, to be 5.4 cm, of which the top 1.4 cm is 2 mm square. The bottom 4 cm, circular in section, tapers from the squared section to a point. The cylindrical handle measures 2 cm in length and 8 mm in diameter, the waisted part being 5 mm in diameter. My replica of this drill is made from a bronze casting containing 90 per cent copper and 10 per cent tin.[21] After shaping and polishing, it was force-fitted into a replica wooden handle. A small bow rotates the drill, after a single turn of the string is made upon the waisted part of the handle, the replica drill being tested upon calcite and harder stones, such as amethyst and carnelian (*Fig.* 8).

Six New Kingdom tombs in the Theban necropolis

Several hundred years later than the Kerma bronze bead drill, a different type of bronze drill is illustrated in six private tombs dating to the

Eighteenth and Nineteenth Dynasties at Thebes, Upper Egypt. In each tomb, craftworkers drill stone beads, each worker operating several drills simultaneously by a single, long bow. In one representation, a driller is perforating two beads, but sometimes three, four or even five beads are being drilled at the same time by one craftworker. These changes not only required fundamental modifications to a Kerma-type drill, but also to the manner in which Kerma single drills were operated. None of the Theban equipment has survived to the present day; only by testing anciently-used bead materials with reconstructed drill-rods, and their driving bow, can the tomb illustrations be brought to life. In this way, the drilling tool's impact upon ancient stone bead production can be assessed.

The first five tombs were constructed during a period of approximately 100 years (ca. 1475–1375 BC), and all date to the Eighteenth Dynasty. The sixth tomb, that of the Nineteenth Dynasty Treasury Scribe of the Estate of Amun, Neferrenpet, was constructed about 85 years later than the last tomb of the Eighteenth Dynasty.

The tomb of Puyemre (ca. 1475 BC, TT 39, reign of Tuthmose III)[22] shows two drillers facing each other seated upon low stools. They both use the same drilling table. Each craftworker simultaneously operates two drills. In the tomb of the Vizier Rekhmire (ca. 1471–1448 BC, TT 100, reigns of Tuthmose III and Amenhotep II)[23] a worker is depicted using three drills at the same moment and, similarly, a worker in the tomb of Amenhotpe-si-se (ca. 1415 BC, TT 75, reign of Tuthmose IV)[24] also operates three drills.

The tomb of Sebekhotep (ca. 1415 BC, TT 63, reign of Tuthmose IV)[25] is of crucial importance. An illustration, removed from the tomb wall in the middle of the nineteenth century, shows two workers each with four drills, and one artisan with three drills. A fragment of a fourth driller is on the left-hand edge of the scene. Another jeweller is polishing beads on a sloping bench, and yet another is threading beads into a collar. In the tomb of the Two Sculptors, Nebamun and Ipuky (ca. 1375 BC, TT 181, reigns of Amenhotep III and IV),[26] a single craftworker simultaneously operates three drills. The tomb of Neferrenpet (ca. 1290 BC, TT 178, reign of Ramesses II)[27] shows two workers, one spinning five drills, the other spinning four drills.

Interpretations of the illustrations

The length of the bow is estimated to be 1.2 m; this is considerably longer than a bow depicted in the Eighteenth Dynasty tomb of Rekhmire for drilling holes into wood.[28] The bow-shaft thickness appears to be 1.5 cm. Also, the multiple bead drilling bow's arc-shape differs from the usual shape of a woodworker's bow, which is shaped like a human arm partially bent at the elbow. All of the operators are shown holding the extreme ends of the bows, with their thumbs or fingers intertwined with the bow-strings. The best depiction of multiple bead drilling occurs in the tomb of Rekhmire.

Norman de Garis Davies commented upon the multiple drilling scene in the tomb of Rekhmire.[29] He noted that the bow-string loops around each of the three yellow-coloured drills in turn, which revolve in the thicker red shafts. From this, it may be assumed that the drill-rods are made of bronze. They are estimated by the author to be 5 mm in diameter and between 20–30 cm in length, and the string to be 2 mm in diameter, if compared with the diameter of the bronze drill-rods. The handles are all closely held together by the driller's left hand. Each drill-rod must, therefore, be rotating in a hole bored into the lower end of each handle. The lower ends of the rods rotate in the holes being drilled into the stone beads. This means that each drill-rod is spinning rapidly, clockwise and then anticlockwise, each end supported in a bearing-hole.

If this interpretation is accepted, then the length and the construction of the bow now become apparent. The handles are similar in length, about 30–40 cm, and taper from the top to the bottom. Their average diameter appears to be about 1.5 cm, at the lower ends. My experiments showed that this diameter allows up to five handles to be gripped in a line with one hand.

In the tomb of Rekhmire, the operator is seated upon a three-legged stool; the drilling table also possesses three legs. Three-legged tables and stools are stable on uneven floors, and this was found to be essential for the multiple bead drilling tests. The tomb representations of the table-tops do not show how beads were held in place. In some tomb illustrations, the table-top has a considerable thickness. This may be an edge board, fixed around each side of a square top. The inside of these table-tops may have been hollow and filled with mud, into which beads were pushed part-way in straight lines. These would be separated by a similar measurement to the separation of the drill-rods when all spinning in their respective handles.

Three out of the six paintings, the tombs of Sebekhotep, Nebamun and Ipuky and Neferrenpet, have bowls with an implement projecting from them. Amenhotpe-si-se has the bowl, but no implement. The bowls are either shown upon, above or under the drilling tables. The bowls probably held the grinding medium, a thin, runny paste made, possibly, from the waste powders obtained from the drilling and sawing of stone with sand abrasive; in my experiments the addition of muddy water made the test paste perfect for drilling beads.

The tomb of Puyemre depicts what is probably a rope passing over the table. The two projections on the rope may be large knots. Each operator has a foot over one end of the rope, which keeps it taut. This rope seems to be holding the table steady, while the two drillers operate their bows; W. Wreszinski[30] also suggests that this is the rope's purpose. If the two projections are indeed knots, then these would bring pressure to bear upon the table, *and anything within it*. The Rekhmire driller's outstretched left leg and foot appear to be holding the table's leg down. The craftworker in Nebamun's and Ipuky's tomb could be holding the table steady between the knees. Therefore, in three separate tombs, and in three distinctive ways, the drillers kept their tables from rocking to and fro due to the motion created by the drilling action.

Making reconstructed tools

The bow-shaft could have been made from a slim, seasoned, arc-shaped branch or a reed cane. My reconstructed bow-shaft was manufactured from a 1.5 cm-diameter cane, 120 cm long, bent into an arc and left in this position for several hours; although the cane relaxed a little after release, it substantially retained its new shape. Tests were also conducted with a 1.5 cm-diameter arc-shaped branch. Both types of bow-shaft possessed similar controlled resistance to bending, which placed a reasonable amount of tension upon the string.

The three bronze drill-rods were cast into vertical, open moulds in sand, made by a 5 mm-diameter rod of wood. The melted bronze consists of 95 per cent copper and 5 per cent tin, by weight, the drilling ends being finished by grinding them on a piece of sandstone. The points originally measured 2 mm in diameter, for the drilling tests on calcite and serpentine, but later, for the tests upon the quartz and the amethyst specimens, one point was ground to a diameter of 1 mm. The top ends of the rods automatically become rounded during casting, due to the contraction of the bronze into a meniscus. This rounded contour is given a final polish, acting as a perfect bearing within the hole in the wooden handle.

A set of three handles and a set of five handles were made from suitably seasoned tree branches. A red-hot drill-rod burnt a hole into each handle, about 10 mm deep; this technique ensured that each hole was slightly larger in diameter than its drill-rod, for clearance. The rounded end of the drill-rod created a concave bearing surface into the wood, the carbonized layer facilitating the drill-rod's rotation within its bearing hole. Carbon acts as an efficient lubricant and ancient craftworkers knew of carbon's lubricating qualities: when making fire, the rotated wooden fire-stick, and the hole in the wooden block, became carbonized, causing a rapid decline in hot wood-ash production.

As previously mentioned, ancient artists have provided no clues as to how the beads are fastened to the tables; each representation shows the drilling table in side elevation. There is no sign of any beads projecting up from the tops of the tables: they could have been similar to the reconstruction depicted in *Fig.* 9. The reconstructed table was made with a hollow top, which could have been filled with mud, similar to the manner in which mud bricks were made in a wooden frame.

Experiments with beads set into mud which is then allowed to harden, demonstrate that they may conveniently be set in a line and spaced apart to match the distance between each drill-rod. Also, any bead size or shape can be coped with in this manner, and may be placed at whatever angle is required for each perforation. After drilling, small beads may easily be broken out of the dried mud in an undamaged state. Further, all long beads can be broken out after drilling half-way, and reset into a new mud block for the second half of the drilling operation. The experimental wet drilling abrasive did not soften the mud block's hold upon the beads. Other methods may have been in use during ancient times. For example, large and small beads could have been forced into holes drilled into the top of the wooden table. However, as the craftworker was aware of mud brick manufacture, the technology could have been adapted for multiple bead drilling. The experimental mud block shrank as it dried within the reconstructed 20 cm-square hollow table-top, opening up a gap of 10 mm

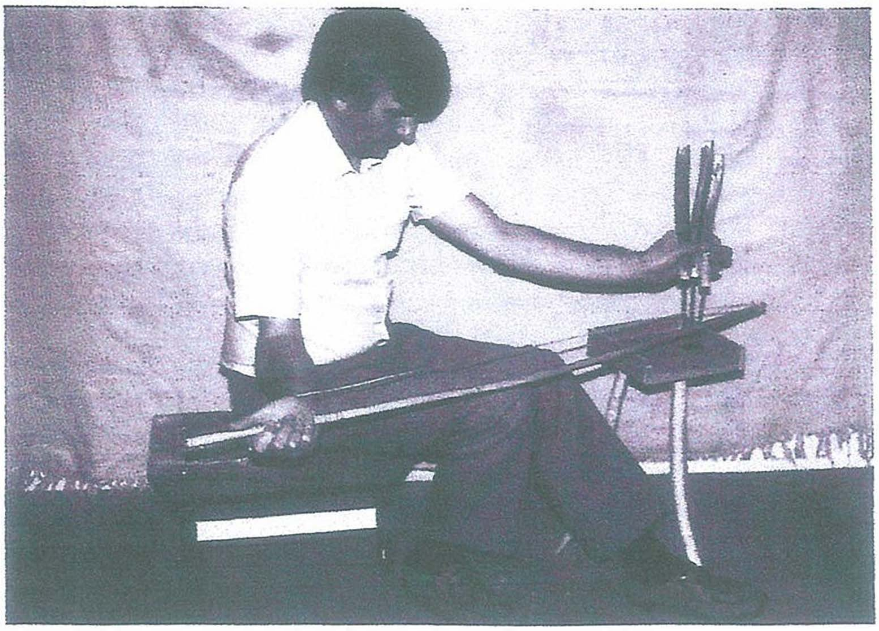

Figure 9. The reconstructed set of three drill-rods in operation.

on all sides. The Puyemre rope, with its two knots, may have been made to secure such a block, in addition to keeping the table steady.

Demonstrating single and multiple bead drilling

The replica single bead drill works very well, as can be seen, and achieves the perforation of hard stone beads. The assembly of the reconstructed multiple drilling equipment, using three drills simultaneously, followed the scene in the tomb of Rekhmire. For demonstration, three pieces of calcite were carved into spherical beads, and a pointed flint tool used to bore a small depression into each of their surfaces for centralizing the drills' points. The beads were set into a stiff mud mixture in a line, approximately 1.5 cm apart. After drying, each bead became immovably set into the mud block.

Craftworkers needed to assemble their tools by themselves. Experiments suggest the following way in which this could be done. Firstly, slacken the bow-string on the bow-shaft and make a single turn around each of the drill-rods; the turns are all in the same direction. In ancient times, a bow-string was securely fastened to the end of the bow-shaft furthest away from the operator, but the other end of the bow-string probably needed a loop, or a noose, which loosely fastened around the bow-shaft where the artisan's right hand held it. Sliding the loop toward the centre of the shaft would slacken the bow-string. This loop technique was adopted for the experiments. The loop was then moved towards the end of the bow-shaft, placing tension upon the string.

Secondly, engage each rod's drilling points into the depressions in the beads' surfaces. Thirdly, locate each handle onto the top end of its drill-rod and, finally, spoon runny paste onto the beads' points. The left hand tightly grips the handles together, with the thumb in front and the fingers behind.

The right hand now clasps the end of the bow-shaft, the string passing *behind* the thumb. The tension induced by pulling the thumb backwards ensures that each drill-rod is gripped by the bow-string. An examination of the Rekhmire representation shows the operator with the right arm outstretched, with the drill-rods at the opposite end of the bow.

I could then drive the bow forward until the hand reached the mid-chest position, that is, with the elbow almost fully bent, a distance of approximately 60 cm. In order to keep the bow travelling in a straight line, the right wrist progressively bends *backwards* on the inward stroke and, conversely, *forwards* on the outward stroke. All of the drill-rods revolved simultaneously. At the end of the return stroke, the arm became almost fully straightened.

Previous experiments determined that the tension imposed by the string on the drill-rods is critical. Should the tension be too great, the drill-rods do not revolve. Conversely, if the tension is too weak, the string slips around

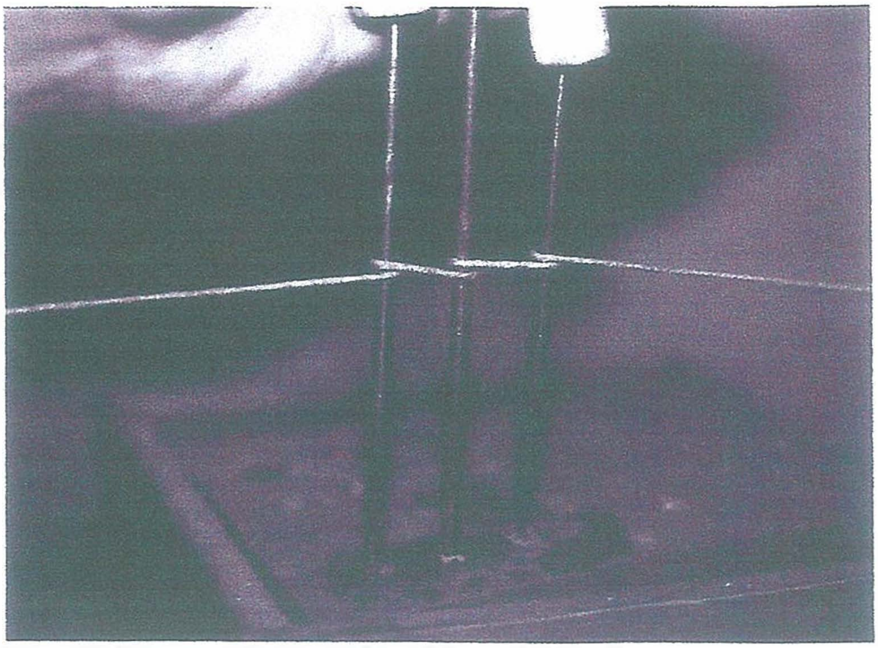

Figure 10. Close-up of the bow-string driving each drill-rod.

the drill-rods without turning them at all (*Fig.* 10). However, even correctly tensioned string can slip around the bronze drill-rods, as they become polished over extended periods of operation. A coarse piece of sandstone soon makes the rods' surfaces rough enough for the string to grip the metal. It is quite noticeable that, whilst the bow is being driven to and fro, the right-hand thumb automatically adjusts the tension on the string.

Calculations based upon a stroke length of 60 cm, a rod diameter of 5 mm and a stroke rate of 40 per minute indicate that each rod revolves at 1,500 revolutions/minute. This, of course, takes no account of the extremely rapid acceleration and deceleration at the beginning and ending of each stroke. A stroke rate of 40 per minute is found to be the optimum frequency necessary to keep up high drill-rod rotations, and also to maintain the drilling action without instability or undue friction to the string. The actions necessary to maintain drilling are not too tiring. The weight the left arm naturally places upon the drill-rods is enough to make them cut into the stone.

It is clear that each drill-rod needs its own handle, rather than one large handle containing all the bearing holes. In this scenario, any drill-rod changing its length over a period, due to excessive wear in relation to the other drill-rods in the same group, would rotate in its bearing hole, but no pressure could be exerted upon that rod. Consequently, no further penetration would take place. With independent handles, this difficulty is remedied by posture changes from time to time, which allows an individual handle to change its vertical position relative to the other handles.

It is likely that the diameter of the ancient string in use for multiple bead drilling bows was 2 mm, operating on drill-rods measuring 5 mm in diameter. The ratio of string diameter to drill-rod diameter (2 mm to 5 mm) gives good rotational results, even with five rods. There can be no doubt that the New Kingdom craftworker possessed the ability to cast 5 mm-diameter drill-rods. The test drill-rods were used in a fully annealed state; this better allowed the tiny angular quartz fragments in the abrasive paste to become embedded into the metal.

It is noticeable that the point of each test drill changes into a blunted, rounded shape, caused by the wobbling action of the drills. The drill-point and the perforation walls become striated by the tiny quartz fragments – mostly between 50–150 microns across – in the abrasive paste, but these striations are extremely fine in appearance.

Workers depicted in the tomb scenes are shown operating two rods (Puyemre), three rods (Rekhmire, Amenhotpe-si-se, Sebekhotep and Nebamun and Ipuky), four rods (Sebekhotep and Neferrenpet) and five rods (Neferrenpet). The test use of five drill-rods proved to be possible.

Results

The table below summarises the experimental cutting ratios and rates for perforating single bead materials (replica Kerma drill):

bead material	*diameter of hole (mm)*	*depth of hole (mm)*	*drilling time (minutes)*	*drill-rod length lost (mm)*	*ratios bronze : stone*	*cutting rates (mm^3/hour)*
calcite	2	5.0	30	>0.05	1 : >100	30
serpentine	2	1.5	15	0.30	1 : 5.0	18
quartz	1	0.5	12	0.20	1 : 2.5	2
amethyst	1	0.5	15	0.20	1 : 2.5	2

Experimental single bead drilling times, ratios of bronze drill to stone wear rates, and cutting rates.

Table 3. Replica Kerma single bead perforation results – average of all experiments.

The table below summarises the cutting rates for simultaneously perforating three beads (reconstructed Theban multiple bead drilling tool):

bead material	*diameter of hole (mm)*	*hole depth (mm)*	*single rate (minutes)*	*mass-production rate (minutes) one bead produced per*
calcite	2	10	60	20
serpentine	2	10	100	33
quartz	1	10	240	80
amethyst	1	10	300	100

Experimental mass-production bead drilling rates (in minutes) for calcite, serpentine, quartz and amethyst, compared with a single mass-production drill-rod's perforation time for each bead material and hole diameter.

Table 4. Reconstructed Theban mass-production bead perforation results using three drill-rods – average of all experiments.

In the tomb of Sebekhotep, the use of four drill-rods could have produced amethyst (hardness Mohs 7) beads at the rate of one per 75 minutes; and the use of five drill-rods could have produced these hard stone beads at the rate of one per 60 minutes. These advanced techniques for mass-producing stone beads, operating in the New Kingdom period at Thebes, greatly reduced the time, and the cost, for the manufacture of jewellery incorporating threaded beads, amulets and pendants.

Conclusions, discussion and implications of the two drilling experiments

The experiments examined in this paper indicate fundamental advances in ancient Egyptian hard and softer stone drilling technology. They suggest that a copper tubular drill was first employed to drill out Predynastic hard and softer stone vessels, the weighted drill-shaft being partially rotated clockwise and then anticlockwise directly by hand. Crucially, beginning in the Third Dynasty, similar copper tubular drills were used to create adjacent touching holes in calcite, granite and other hard stones in order safely to hollow out sarcophagi. But for this purpose, the tubular drill was rotated with a bow, the drill-shaft at the upper end rotating in a hand-held lubricated stone bearing. The experimental use of reconstructed tools for stone vessel manufacture suggests that ancient workers may have suffered from repetitive strain injury to their hands, wrists and lower arms.

Also, artisans grinding stone with sand abrasive risked silicosis, an abnormal condition of the lungs that eventually causes debilitating illness and early death. The use of flint tools for shaping hard stone vessels probably caused flesh and eye injuries due to flying pieces of flint and stone from the vessels.

Comparisons between the single and the multiple bead drills clearly indicate that *one* craftworker could now do the work of several single bead drillers in the same time, thus changing the economics of jewellery manufacture in the New Kingdom period.

The six Theban illustrations show that two important inventive steps must have occurred prior to, or during, the New Kingdom period, wherever this took place. Firstly, the bronze drill-rod became lengthened, its upper end rotating in a lengthened wooden handle: this technological innovation dispensed with the original capstone bearing for the single bead drill, the drill-rod now rotating in a hole drilled into the lower end of the longer handle. The handle was now used as a true handle, instead of a small, waisted piece of wood being force-fitted to a copper or bronze single bead drill. The longer bronze drill-rods could now directly be rotated with the longer bow-string.

Secondly, the technique of driving several drill-rods was introduced; the simultaneous multiple drilling technology being possible because several slim wooden handles can be gripped in a line by a human hand. The development of multiple bead drilling technology caused a lengthening of the bow, coupled with changes in the physiological approach to this type of drilling.

These two differing types of drilling technology, the directly hand-operated and the bow-driven copper or bronze tubular drill for use in the manufacture of stone vessels, sarcophagi, shrines, statuary, and for other objects, and the New Kingdom mass-production system of creating the threading holes in hard stone beads, indicate their key roles in the development of ancient Egyptian civilization. Without the development and employment of these technologies over thousands of years there would have been a considerable reduction to the number and variety of artefacts made from both hard and softer stones.

Due to the erosion of the tubular drills by the coarse sand abrasive, the renewal of many thousands of copper stonecutting tubular drills (in addition to the heavy-duty copper stonecutting saw) consumed a significant proportion of Egypt's total copper production, itself a complicated process involving many workers.

Often in archaeological research, a point is reached where no further information is available on tools and artefacts using the evidence of excavation, the written and illustrative evidence and the extensive scientific methods supporting archaeological research. In these circumstances, archaeological research may be assisted by experiments. In particular, the understanding of tools' constructional methods and materials, whether they still exist or only exist in 2-D representations, together with their uses for making all manner of artefacts in conjunction with systems of manufacture connected with these tools, can be progressed. Tools can be replicated or reconstructed using ancient manufacturing methods and materials for experimental testing and evaluation, and their place in connection with the development of other tools and systems of manufacture more accurately established.

The ability to make replica tools and artefacts, or to reconstruct tools represented in art, requires considerable training in engineering and other related disciplines. The average length of engineering apprenticeship schemes is five years. Within this period, an apprentice's mentors strive very hard to demonstrate and to explain what has to be learnt to make a master craftworker. I was fortunate indeed to have received the wisdom and experience of four masters who themselves had learnt from the generation before them. However, a shortened apprenticeship in the areas of expertise necessary to perform relevant experiments is a feasible option and should be considered as part of project research for undergraduate and for postgraduate students.

A considerable time after I started my technology project, I discovered that many of the crafts I learnt in the middle of the 20th century were practised by the ancient Egyptians, and that therefore it is reasonable to think that an unbroken chain of artisans has spanned the thousands of years, the hundreds of generations, since ancient times and that eventually many of their skills have come through to us.

Acknowledgments

I extend grateful appreciation for the patient teaching given to me during my formative years, and during my mechanical engineering technical apprenticeship, by my mentors: my father, Allen Charles Stocks (mechanical engineer), Fred Power and Joe Tasker (master fitters) and John Smith (master blacksmith). Without these four expert artisans I could never have undertaken my extensive ancient Egyptian technology project.

Notes

[1] Hoffman 1980, 207.

[2] Petrie 1917, 6.

[3] Woolley 1934, II, 380; Reisner 1931, 180; Lucas and Harris 1962, 74.

[4] Stocks 1993, 597; 2003, 103–38.

[5] Quibell and Green 1902, 6, pl. LXII.

[6] Davies 1943, I, 49, note 22.

[7] Quibell and Green 1902, pls. XXXII, LXII.

[8] Firth, Quibell and Lauer 1935–36, I, pl. 93.

[9] Gardiner 1976, 519, sign U25; Murray 1905, I, 65, pl. XXXIX; Borchardt 1897, 107.

[10] Blackman and Apted 1953, V, pl. XVII.

[11] Gardiner 1976, 518, sign U24; Davies 1943, II, pl. LIV.

[12] Davies 1902, I, pl. XXIV.

[13] Stocks 1993. 598.

[14] Duell (ed.) 1938, I, pl. 30.

[15] Woolley 1955, fig. 5.

[16] Petrie 1917, 45, pl. LII, 61.

[17] Provenance and date unknown.

[18] Lucas and Harris 1962, 41.

[19] British Museum 920.

[20] Reisner 1923, 93–4.

[21] Stocks 1989, 527.

[22] Wreszinski 1923, I, pl. 154; Davies, 1922, I, pl. XXIII.

[23] Newberry 1900, pls. XVII, XVIII; Wreszinski 1923, II, pl. 313; Davies, 1943, II, pl. LIV.

[24] Wreszinski 1923, II, pl. 242; Davies 1923, II, pl. X.

[25] British Museum 920.

[26] Wreszinski 1923, II, pl. 360; Davies, 1925, pl. XI.

[27] Wreszinski 1923, I, pl. 73, a, b.

[28] Davies 1943, II, pls. LII, LIII.

[29] Davies 1943, I, 49.

[30] Wreszinski 1923, I, pl. 154.

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35

Scientific evaluation of experiments in Egyptian archaeology

Denys A. Stocks

I first met Professor Rosalie David in 1979 as an enrolled member of her introductory course in Egyptology. The meeting with Rosalie changed the direction of my life, for in 1980 I enrolled for her Certificate in Egyptology course, which later led to a research degree, a teaching qualification and a position as a teacher of design and technology, and of history.

About ten years earlier I had commenced an ancient Egyptian technology research project incorporating craftworking techniques, which involved the manufacture of replica and reconstructed tools made from wood, stone, copper, bronze and other materials for test and evaluation. I constructed a home workshop containing a furnace for casting the copper and bronze tools, the first ones cast being replicas of anciently designed flat and crosscut tapered chisels.

During an interview with Rosalie, mainly to discuss the subject area for the Certificate in Egyptology dissertation, I showed to her some of my cast copper chisels, and she mentioned that they were similar to copper chisels in the basement store and in the display cases of the Manchester Museum. I also pointed out six indentations on each replica chisel's edged taper, created by a hardness testing machine. We discussed the use of scientific methods to assist with the evaluation of a chisel's hardness and its associated capability for cutting types of wood and stone. Rosalie expressed a commitment to scientific methods for supporting future evaluations of experiments completed as part of my ancient Egyptian technology research project. In 1986, she kindly made contacts within the University of Manchester on my behalf, which resulted in an invitation by the late Professor Barri Jones to enrol for the degree of Master of Philosophy in the Department of Archaeology: Rosalie became my supervisor for this degree.

This chapter is presented in honour of Rosalie for her much appreciated help in developing my ancient Egyptian technology project. It summarises three areas of my research that benefited from extra evaluations using scientific methods, beginning with the experimental manufacture and test of replica copper and bronze chisels to establish what resistant materials could be cut by ancient chisels. As a matter of interest, particular scientific principles that ancient craftworkers employed in the construction and use of their tools, and in their manufacturing technologies, are discussed.

Hardness and cutting comparisons between experimental and ancient copper and bronze chisels

The experimental manufacture of twelve test copper and bronze chisels commenced by accurately weighing copper and varying quantities of other constituent metals, such as iron, tin and antimony, and then casting each individual chisel in a clean crucible. Upon becoming cold, each casting immediately received a sequential identity project number punched into it before its designated flat or crosscut taper was hammered to shape. This number referred to its metallic content, its scientifically determined hardness and its performance in cutting different wood and stone types (Stocks 1988, II: appendix C, 1–4; appendix H, 1–6).

The casting of the chisels took place in open sand moulds. Six chisels were designated as copper tools, project nos. 1–4, 6 and 26, and six chisels designated as bronze tools, project nos. 9–11, 18, 22 and 25 (see Table 35.1 for contents of both chisel types). In particular, the three bronze chisels 18, 25 and 22 contain 8 per cent, 10 per cent and 12 per tin content respectively. Some preliminary hardness testing of project bronze chisels, containing between 8 per cent and 12 per cent tin, indicated twin advantages of hardness and durability for these tools.

As an integral part in determining each chisel's capability to cut resistant materials, its edged taper received a hardness test after *cold* hammering the metal into shape, this being the only way in which to work-harden non-ferrous metals (Rickard 1932, I: 116), in contrast to ferrous alloys, such as steel, which require high temperatures. Red-hot copper and bronze become brittle because of changes to their crystal structures at elevated temperatures (Rickard 1932, I: 116). For example, a project-manufactured bronze chisel, containing 5 per cent tin, when raised to a bright red heat and hammered immediately, fractured into several pieces (Stocks 1988, I: 77). Copper and bronze tools – chisels, adzes and axes – normally require these metals to be annealed during the hammering process in order to restore malleability and to delay cracks from forming, particularly for bronze tools containing significant amounts of tin. However, metallurgical studies have revealed that ancient tools were sometimes heavily cold-worked without any annealing (Maddin *et al.* 1984: 39). Annealing is achieved by heating the metal to a dull red heat and allowing it to cool slowly in the air: quenching in cold water is inappropriate for non-ferrous metals. However, the project chisels were hammered to shape without annealing in order to obtain the highest possible hardness results.

In order to determine each numbered chisel's hardness, testing was carried out on its hammered taper using a Vickers pyramid hardness testing machine: hardness is established by the use of an inverted, pyramid-shaped diamond indenter placed under a known load for a known fixed time. Six indentations are made into a chisel's taper. The Vickers Pyramid Number (VPN), resulting from a mathematical equation, is an expression of the relationship of a known force upon a known area, and the higher the number obtained the harder the specimen. The average of the six values obtained from the six indentations gives the final VPN (see Table 35.1).

The hardness tests show that the six replica copper chisels range from VPN 132 to VPN 167, being harder than annealed (softened) mild steel of hardness VPN 131 (Rollason 1939: 3, table 1). The six bronze chisels range from VPN 161 to VPN 247, with some of them exceeding the hardness of cold-rolled (hardened) mild steel of hardness VPN 192 (Stocks 1988, II: appendix B). Bronze chisel project nos. 22 and 25 are harder than modern unworked chisel steel of hardness VPN 235 (Rollason 1939: 3, table 1), but hammered chisel

Table 35.1 Hardness results for replica copper and bronze chisels

Chisel no.	Metal type	Chisel taper	Cu %	Sn %	Fe %	Pb %	Sb %	VPN
1	copper	flat	98	0.5	1.5	–	–	132
2	copper	flat	96	1.1	2.9	–	–	134
3	copper	crosscut	96	1.5	2.5	–	–	146
4	copper	flat	96	1.8	2.2	–	–	154
6	copper	flat	96	2.0	2.0	–	–	167
26	copper	flat	98	0.6	0.5	0.7	0.2	140
9	bronze	crosscut	97	3.0	–	–	–	161
10	bronze	crosscut	95	5.0	–	–	–	180
11	bronze	flat	93	7.0	–	–	–	188
18	bronze	flat	92	8.0	–	–	–	232
25	bronze	flat	90	10.0	–	–	–	239
22	bronze	flat	88	12.0	–	–	–	247

Abbreviations: Cu = copper, Sn = tin, Fe = iron, Pb = lead, Sb = antimony

Note: The table is organised, for bronze chisels, to show increasing proportions of tin and not according to sequential project numbers.

steel's hardness is VPN 800 (Rollason 1939: 3, table 1). During the project, a test to destruction of a 10 per cent tin in bronze casting, using hammer blows of considerable force, soon caused it to fracture, the highest hardness VPN 256 being recorded.

The testing of each replica copper and bronze chisel for cutting materials, such as types of stone, could now be related to that particular chisel's known metallic content and its hardness VPN. In this study, composition analyses of some *ancient* copper and bronze chisels would provide a guide to *estimated* hardness numbers for them, and that these estimated hardness numbers would indicate ancient chisels' capabilities for cutting particular stone types when compared with the cutting tests performed by replica copper and bronze chisels of broadly similar metallic content.

Stonecutting tests commenced with the replica copper flat and crosscut tapered chisels. The stones utilised for test included two sedimentary types, red sandstone and soft limestone (both hardness Mohs 2.5), calcite (Mohs 3–4), hard sandstone and hard limestone (both Mohs 5) and rose granite and diorite (both Mohs 7). All six copper chisels cut the two sedimentary stones well, but cutting calcite, hard sandstone, hard limestone, rose granite and diorite demonstrated that all of the chisels suffered immediate blunting and jagged dents to their edges, discounting them as cutting tools for these stones.

The cutting tests with the bronze chisels on rose granite, diorite, hard sandstone and hard limestone demonstrated that all six chisels sustained serious damage. The two bronze chisels, project nos. 10 and 11, could just cut calcite, but experienced unacceptable damage. Only the bronze chisels 18, 22 and 25 cut calcite reasonably well, but required sharpening at intervals not consistent with the efficient use of the tools. Consequently, it is likely that the hardest ancient bronze chisels lost metal at a rate that was unacceptable to ancient craftworkers. The bronze chisels also cut red sandstone and soft limestone with ease, both the softer copper and bronze chisels sustaining slight wear over time. The test cutting of hard and soft woods with project copper and bronze chisels shows that all of these tools possess superior hardness to all woods, requiring only infrequent sharpening of their cutting edges.

As part of my MPhil research I studied several metal chisels found by Sir Flinders Petrie at 12th Dynasty Kahun (Petrie 1890: pl. XVII, 4; Petrie 1891: pl. XIII, 14, 16; Petrie 1917: 20, pl. XXII, C79; Stocks 1988, I: 45–6, 79, fig. 10, a–c). G. R. Gilmore's (1986: 458) composition analyses of three of the Kahun chisels, J. H. Gladstone's (1890: 227) composition analysis of a fourth Kahun chisel and composition analyses for a New Kingdom chisel (Colson 1903: 191) and for two chisels from the 12th and 18th Dynasties respectively (Sebilian 1924: 8) enabled estimates of the hardnesses of two ancient copper chisels and five ancient bronze

Table 35.2 Hardness estimates for some ancient copper and bronze chisels

Number	Metal type	Cu %	As %	Sn %	Fe %	Estimated VPN
1	copper	96.00	2.37	–	0.54	150–60
2	bronze	93.00	0.94	3.33	1.31	165–75
3	copper	97.00	1.11	0.61	–	140–50
4	bronze	96.35	0.36	2.16	–	160–70
5	bronze	84.60	–	13.30	0.30	245–55
6	bronze	92.60	–	7.40	–	210–20
7	bronze	88.00	–	12.00	–	240–50

Abbreviations: Cu = copper, As = arsenic, Sn = tin, Fe = iron

Note: Analyses 1–3 (Gilmore 1986: 458); analysis 4 (Gladstone 1890: 227); analysis 5 (Colson 1903: 191); analyses 6, 7 (Sebilian 1924: 8). Blanks indicate elements not determined.

chisels to be made. This allowed assessments of what wood and stone types these chisels could cut when compared with the project manufactured copper and bronze chisels' cutting capabilities. (See Table 35.2 for the composition analyses and for the hardness estimates).

No project replica chisel contains arsenic, although composition analyses of some ancient chisels record this metallic element (Table 35.2). J. Maréchal (1957: 132–3) conducted hardness tests on three copper and arsenic alloys. They contained 4.2 per cent, 5.94 per cent and 7.92 per cent of arsenic and reached hammered hardness VPN 195, 220 and 224 respectively. These arsenical copper alloys all exceed the hardness of cold-rolled mild steel. The third result shows reasonable hardness comparability to the writer's project no. 18 bronze chisel containing 8 per cent tin, hardness VPN 232, as opposed to Maréchal's 7.92 per cent arsenical copper of hardness VPN 224.

In conclusion, the project hardness results recorded for the experimentally manufactured copper and bronze chisels with their known metallic compositions and cutting abilities, together with Maréchal's three arsenical copper hardness results and the scientific methods for determining the composition analyses of some ancient copper and bronze chisels, allowed estimates to be made for the hardness and cutting capabilities of the group of ancient copper and bronze chisels listed in Table 35.2. Evaluation of this research suggests that no experimental copper or bronze chisel for this study, nor *any* ancient copper or bronze chisel, could effectively cut stone other than red sandstone, soft limestone, gypsum (Mohs 2) and steatite (Mohs 3). All of the experimental chisels cut hard and soft wood types easily, indicating that ancient copper and bronze chisels were practical for this purpose.

Fitting limestone blocks into the Great Pyramid of Giza

At Giza during the 4th Dynasty Khufu built his Great Pyramid (Plate 16) using large limestone core-blocks and casing-blocks for its construction. Not only did Khufu's masons make each block's top and bottom joint surfaces accurately flat, but they are also parallel to each other and truly horizontal towards the pyramid's central axis and along each of the four sides. Parallelism between each block's top and bottom joint surfaces is essential to guarantee the pyramid's structural stability. How did craftworkers achieve such remarkable accuracy in fitting millions of limestone blocks into Khufu's pyramid? There are several clues helping experimental research into this enigma.

Firstly, Flinders Petrie made careful measurements of the rising joints of several of the remaining large casing-blocks at the base of the northern side of the Great Pyramid. The measurements revealed that 'The mean thickness of the joints of the north-eastern casing-stones is 0.02 inches [0.5 mm], and therefore the mean variation of the cutting of the stone from a straight line and from a true square is but 0.01 [0.25 mm] on a length of 75 inches [1.9 m] up the face …' (Petrie 1883: 44).

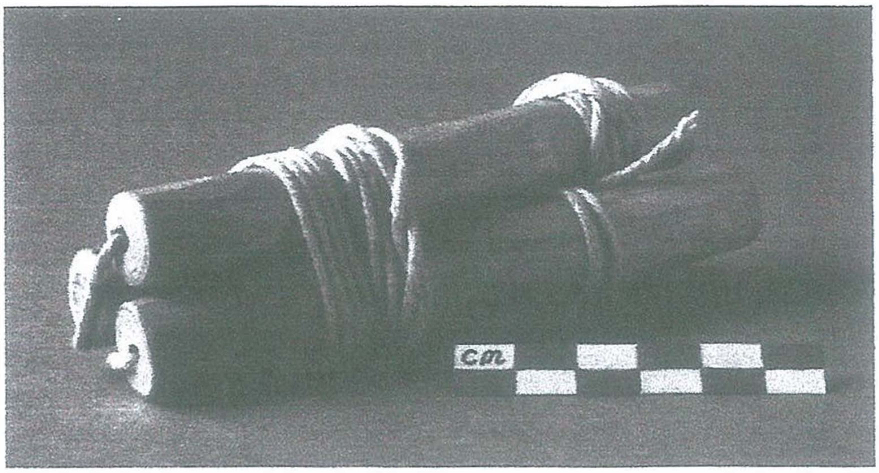
Secondly, S. Clarke and R. Engelbach (1930: 100) also examined these casing-blocks. They noticed that the tops of the blocks were dressed *after* they had been laid, and that this procedure sometimes involved part of a core-block lying immediately behind a casing-block. This observation has considerable relevance when considering the processes of producing and testing the flatness of the top surfaces of both core-blocks and casing-blocks.

Petrie's measurements of large casing-block joints, the cutting of an immense number of truly horizontal and truly vertical block surfaces, the parallelism of all blocks' top and bottom surfaces and the experiments with replica tools (Stocks 1988, II: 274–92, Stocks 2003a: 572–8; Stocks 2005: 4–9) indicate that three known surface flatness and orientation testing tools existed at the Great Pyramid site, even though these tools have never been found at 4th Dynasty Giza. A set of three wooden rods and string, used for testing surface flatness, has been found at 12th Dynasty Kahun (Petrie 1890: 27). Two model tools were found in the 19th Dynasty tomb of Senedjem (Theban tomb 1) at Deir el-Medina, each fitted with a plumb line, being the wooden frame for testing horizontal surfaces, shaped like the letter A, and the wooden frame for testing vertical surfaces, shaped like the letter F (Petrie 1917: pl. XLVII, B57, 59).

In the 18th Dynasty tomb of Rekhmire (Theban tomb 100) at Thebes, an illustration (Davies 1943, II: pl. LXII) depicts the testing of a block's vertical surface flatness between cutting and dressing operations, which is achieved by holding two short rods of wood upright on the surface, a string being tautly stretched between the tops of the rods. A mason holding a third rod of equal length against the string shows how much stone needs to be pared away at that point. Other ancient evidence (Petrie 1909: 72) suggests that, after each surface test along the string's length, a craftworker's finger dabbed red ochre on the indicated higher places, these probably being removed with flint scrapers and sandstone grinders; the rods and string would similarly test and direct adjustments to the whole surface until the third rod just touched the underneath of the string.

The 12th Dynasty set of three rods and string is displayed in the Manchester Museum (acc. no. 28). Petrie measured the rods (Petrie 1890: 27) and found that their lengths 'are 4.96 inches [12.6 cm], equal within two or three thousandths of an inch [0.075 mm]'. To make each rod of a replica set equal to a tolerance of 0.075 mm, a simple yet effective outside calliper consisting of two stones firmly set opposite each other ensures that the three rods, when each precisely fits lengthways into the gap, are indeed a *matched* set (Stocks 2003b: fig. 7.11). Measurements with a vernier calliper confirm that all three rods are equal in length within a tolerance of plus or minus 0.05 mm, supporting the probable use of an ancient outside calliper (Figure 35.1).

Tests, measurements and mathematical calculations (Timoshenko and Young 1956: 162–7) with the replica rod set used upon a known flat surface demonstrated that the taut string, over a distance of 120 cm, created a catenary curve possessing maximum sag of 0.25 mm at the string's central position. This meant that the top surfaces of core-blocks and casing-blocks, always accurately flattened and directed to be truly horizontal with the A-frame *after* blocks had been laid into position, became slightly concave. It is likely that the bottom surface of a core-block or casing-block needed to be dressed flat while in a temporarily reversed position (top surface uppermost) before being hauled up



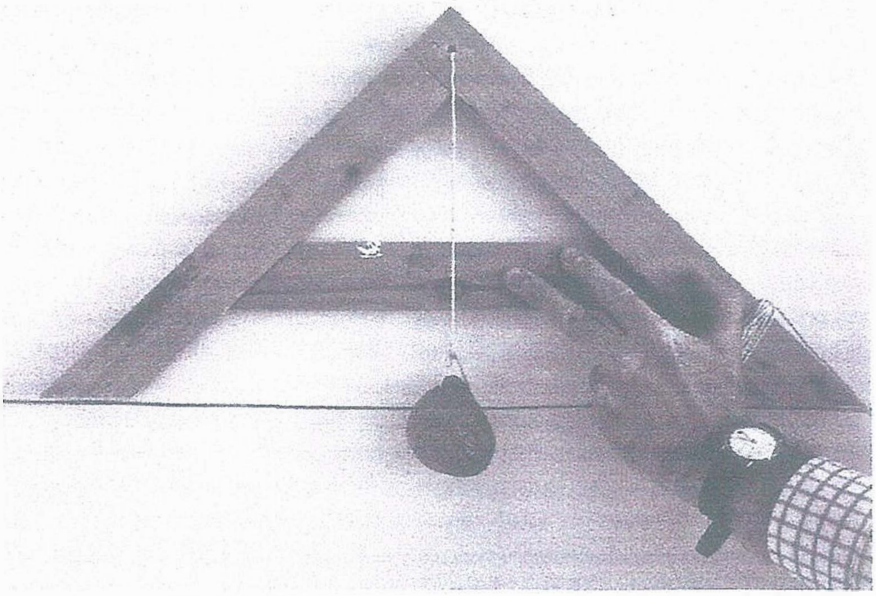
35.1 Replica rods and string set. (Photograph by the author.)

to the pyramid, turned over and laid on the blocks' prepared surfaces below it. A bottom surface of a block dressed and tested with rods and string in an upper horizontal position would also become slightly concave. However, a dressed and tested vertical surface, as seen in the tomb of Rekhmire, would remain truly straight, as a string stretched between the rods would sag not towards it, but downwards to the ground under the influence of gravity.

These procedures guaranteed that the top and bottom surfaces of any block became automatically parallel, an absolute necessity for the pyramid's construction. The gypsum mortar used for sliding a block over a lower block filled slight hollows between the blocks' surfaces, later setting hard and evenly transmitting the weight of an upper block upon supporting lower blocks' surfaces. This phenomenon prevented the blocks from cracking under load.

Henry Gorringe (1885: 83) measured one of the Luxor temple granite obelisks which is now displayed in Paris. He noted that the obelisk's north-west face, as it originally stood in the Luxor temple before its removal, is longitudinally convex, and that the opposite south-east face is longitudinally concave; the obelisk is 25 m long. Over this length, the convex north-west face has a maximum deflection of 2 cm from a straight line, while the concave south-east face has a maximum deflection of 1.27 cm from a straight line. Mathematical calculations confirm that, over a length of 25 m, a tension of 14 kg force in a 2 mm diameter string allowed it to sag 1.27 cm at its central point. The obelisk's finished surface would follow the string's catenary curve and become concave. The south-east face's concavity indicates that its surface originally occupied the quarry's floor, before extraction. The longitudinal convex surface on the opposite face may be explained by measuring from the concave face, all along it, and marking a line on each of the two opposite adjacent vertical faces and, after release of the obelisk from its bed, dressing to the lines to complete the fourth, now convex, face. Measurements and the transposition of mathematical formulae based on the scientific laws of gravity allow the calculation of the precise forces, and the catenary curve characteristics, applied to the rods and string sets used thousands of years ago by craftworkers.

Fashioned from three pieces of wood in an 'A' shape for testing horizontal surfaces (Stocks 2003b: fig. 7.2), the replica frame's plumb line hangs from a hole drilled into the apex (see Figure 35.2). In calibrating a replica tool, the frame's two free ends need just to touch the surface of still water, a vertical mark being made on the horizontal bar exactly behind the hanging plumb line. Reasoning skills are likely to have suggested to ancient craftworkers that still water equated to the flat, horizontal limestone block surface required to build the pyramid, reinforced by knowledge of irrigation techniques that highlighted one of still water's characteristics, a flat horizontal surface in all directions. Further, craftworkers probably reasoned that plumb lines always hang vertically to the flat

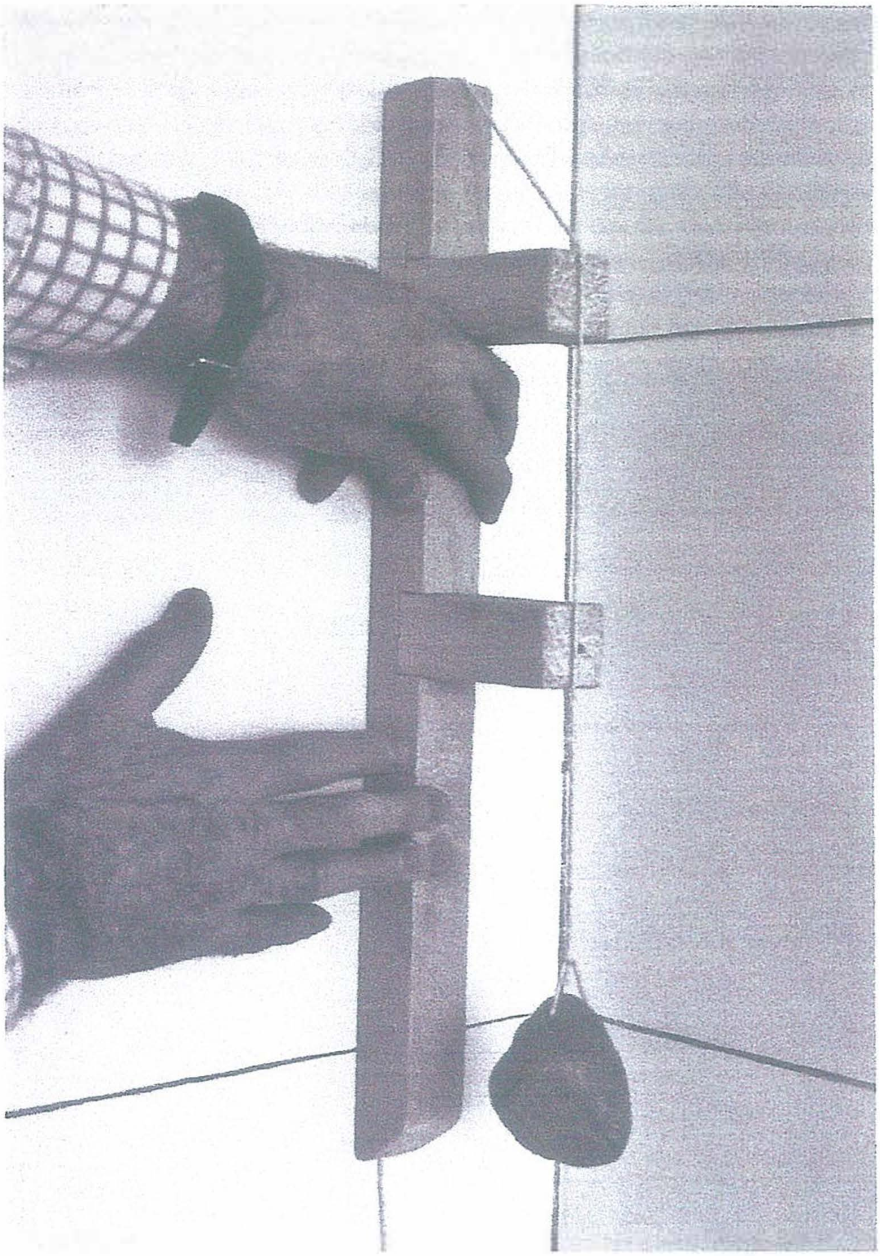


35.2 Replica A-frame. (Photograph by the author.)

surface of still water. The water calibrated replica A-frame, when employed to test two adjoining core-blocks' horizontal surfaces at the Great Pyramid (undertaken with the kind permission of the Supreme Council for Antiquities), demonstrated that the plumb line hung directly over the calibration mark, proving that the blocks are still precisely horizontal and suggesting that craftworkers used the still-water method accurately to calibrate the frame for testing horizontal surfaces in ancient times. The replica rods and string verified that these particular blocks are still accurately flat.

A replica vertical testing F-frame (Stocks 2003b: fig. 7.3) needs the two horizontal pieces to be of exactly the same length, using the outside calliper to achieve this requirement *after* firmly fastening them to the vertical length of wood (Figure 35.3). A hole drilled in the top of the vertical piece, and another hole drilled at an angle of forty-five degrees through the end of the upper horizontal piece, permitted the plumb line to be threaded through the two holes, leaving the line hanging freely against the lower horizontal piece when truly vertical. Provided that each piece of timber was accurately made and fitted together, using an outside calliper for final adjustments, ancient instruments automatically became calibrated at the end of the construction process.

A test with the replica F-frame upon the exposed joint-face of a large casing-block at the Great Pyramid showed that it had been made truly vertical, the



35·3 Replica F-frame. (Photograph by the author.)

plumb line just touching the upper and lower wooden pieces of the F-frame, indicating its use for building this pyramid. The replica rods and string set verified that the casing-block's joint-face is truly flat, suffering no discernible concavity. Bringing two casing-blocks together, their rising joint surfaces truly flat and truly vertical to the already prepared bottom surfaces, achieves the joint accuracy seen today.

The experimental use and evaluation of the three calibrated replica tools demonstrate that they are capable of directing stone block surface and orientation accuracy similar to observed surface and orientation accuracy for blocks in the Great Pyramid, and the verification of several Great Pyramid blocks' surface flatness and orientation with the replica tools strongly suggests that ancient calibrated rods and string sets, A-frames and F-frames existed in the early 4th Dynasty at Giza.

Sliding technology for stone blocks and for inclined ramps

Ancient Egyptian masons mitigated the effects of friction and gravity for sliding heavy limestone blocks by employing gypsum mortar as a lubricant (Edwards 1986: 284). For reducing friction between the runners of a loaded sledge on level surfaces and on shallowly inclined ascending ramp surfaces, craftworkers probably utilised a wetted, compacted clay or lime marl track (Newberry 1895, I: pl. XV; Lehner 1999: 641), but not for moving objects down steeper descending tomb corridor surfaces.

In scientific terms (Timoshenko and Young 1956: 50) the friction that must be overcome to move any block is proportional to the coefficient of friction, μ (mu), and the Normal force, N. (The coefficient of friction is a function of the type of surfaces in contact and the Normal force is the vertical force of gravity acting on the block.) The force F required to move a block is $F = \mu N$. If F is taken as the force necessary to *start* sliding, μ is called the coefficient of *static* friction. If F is taken as the somewhat smaller force necessary to maintain sliding, μ is called the coefficient of *kinetic* friction: only static friction is considered here.

The coefficient of static friction is the tangent of the angle of a ramp on which a block just starts to slide down. It can, therefore, be measured experimentally. The force required is independent of the area in contact, and, since the weight is fixed, the ease of moving a block can only be altered by changing the coefficient of friction, which is the character of the surfaces in contact. This is what the ancient Egyptians accomplished: they prepared blocks' sliding surfaces to a considerable degree of accuracy, using a lubricant between them, and wetted marl as a lubricant for level and ascending ramp track surfaces.

In order to investigate the sliding characteristics of dry and lubricated horizontal limestone blocks, together with lubricated ascending inclines and dry descending inclines, experiments began with two prepared limestone blocks and a wooden sledge runner. The *dry*, accurately flat surfaces of the prepared experimental limestone blocks were placed in contact, one block above the other, and the bottom block was slowly tilted until the top block just began to slide across its surface (Stocks 2003b: 195–6, figs. 7.17, 7.18), the angle of tilt being thirty-six degrees, and similarly for the dry sledge runner (Figure 35.4). The tangent of this angle gives a coefficient of static friction of 0.73. The test was then repeated with liquid gypsum mortar applied to the bottom block's top surface. The upper block now commenced sliding at an angle of eight degrees, giving a coefficient

35.4 Stone blocks for sliding experiments. (Photograph by the author.)

of static friction of 0.14, and similarly for the sledge runner operating on a wet clay surface.

If the experimentally obtained dry and lubricated coefficients of static friction are respectively substituted in the formula $F = \mu N$, when applied to a base casing-block weighing 16,000 kg (Petrie 1883: 44), it can be shown that just over *five* times less force is needed to start a lubricated block moving than for a similar dry block. Under the laws of friction this reduction factor applies to all blocks, no matter what their weight and area of surface contact.

Hauling a block on a sledge up a ramp required a balance between the force required and the angle at which slippage occurred. The force needed to haul a block up a slope inclined at the angle of slippage is *twice* that required on the flat (Timoshenko and Young 1956: 162–7) lubricated or dry. This fact, and the risk of losing a block through slippage, mean that the ramp should be inclined at less than the angle of slippage. This explains why the angles of slopes for extant ancient Egyptian ascending ramps are less than eight degrees, the angle of slippage for wet marl lubricated sledge runners (Stocks 2003b: 576).

For example, the 19th Dynasty Papyrus Anastasi I in the British Museum (BM 10247) gives measurements for a hypothetical ramp inclined at an angle of five degrees. The causeway in front of Khafre's pyramid is inclined at six degrees (established by the writer for this study). The ramp angle of the unfinished 4th Dynasty mortuary temple of Menkaure is just over seven degrees (Edwards 1986: 280). Two stone-built loading ramps in Lower Nubia have a calculated gradient of seven degrees (Shaw *et al.* 2001: 33–4).

However, ramps steeper than eight degrees could have been in use by workers for *dry* sliding objects downwards, allowing friction and gravity to work in their favour (Stocks 2009: 38–43). An example is the ascending corridor of Khufu's Great Pyramid, sloping at just over twenty-six degrees, down which three granite plug blocks were probably dry-slid to the bottom, this angle of slope being confirmed by the writer for this study. Experiments and calculations demonstrate that moving a heavy object down a ramp's dry surface, even one on a wooden sledge, which inclines ten degrees less than the dry slippage angle of thirty-six degrees requires a relatively small increase of force to overcome friction, thus permitting workers carefully and safely to move a heavy object down the ramp. A safety margin of at least ten degrees of slope angle prevents a resting heavy object on a dry ramp's surface from sliding down it, because of friction continually overcoming the force of gravity.

The application of scientific studies in Egyptology develops fresh areas of research, engaging the interest and expertise of a wider body of people: this enables Egyptologists further to interpret archaeological evidence of many kinds. The value of scientific studies in Egyptology, allied to those of a technological nature, is to reveal new, exciting and important insights into many aspects of ancient Egyptian civilisation.

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