VIII. LITHO-MECHANICS AND ARCHAEOLOGY

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Enduring stone gives us a glimpse of man's earliest constructive activity; it also presents us with unknowns. Can engineering and other physical sciences suggest some answers? Does the monumental stone of Chephren's Pyramid enclose passages and chambers? Alvarez (1), working with a team of U.S. and Egyptian investigators, has applied the special knowledge of nuclear physics, in an example of non-destructive exploration which may be applicable to New World structures. (Alvarez found that no major cavities existed in about one third of the bulk of the pyramid, but the remaining two thirds remain to be studied.) How was monolithic Malinalco carved from the living rock? An engineer has made a case for a method which fits the tangible evidence (2).

In proposing the application of engineering analysis to archaeological problems we wish to make a clear distinction between analysis, tested by experiment, and the very useful and valuable empirical work carried out by investigators such as Rau or McGuire(3). There is no intent to ignore or belittle the many years of experimentation and replicative attempts which on this continent, date back to the days of the Conquest(4).

Our concern with stone will be restricted to litho-mechanics, that is, to three topics each associated with manufacturing: fracture of glasseous materials in tool-making, use of stone fly wheels in drilling, and the manufacture of obsidian ear spools.

Fracture of Glasseous Stone.

Various suggestions have been advanced to explain the apparently consistent nature of fracture surfaces produced by man in the making of stone tools. Thus, for instance, it has been said that the prismatic cores often found in connection with blade-making and other worked obsidian pieces are due to planes of weakness in the material(3). Others have realized that flint, obsidian and other non-crystalline materials universally favored by man for stone tool-making have no preferred orientation. Consequently, the fracture surfaces must be rather the result of the special knowledge and skill of the tool-maker(5). A recent engineering analysis was made by Vaidyanathan(6) who considered that the two techniques most used by the early artisan, impact and pressure flaking, produce directions of fracture surfaces which fall entirely within predictable ranges.

It is a fact that brittle materials have a propensity to fracture when tensil stresses reach critical magnitudes. Tensile stresses are internal tractive or pulling forces per unit area which are largest on planes parallel to principal tensile-stress trajectories. Two examples, using chalk cylinders such as those employed for blackboard writing, will illustrate the nature of fracture along principal tensile-stress trajectories.

Writing chalk, largely calcium carbonate in a compressed form, responds to tensile stresses much like glass: (1) If a blow is struck of sufficient magnitude, squarely at the end of the chalk cylinder held in one's hand, a pressure wave will travel down the cylinder at the speed of sound, with a spherical front which is essentially at right angles to the axis of the cylinder. At the free end of the cylinder the pressure wave will become a reflective tensile wave. Fracture ensues across the cylinder if the tensile stresses are sufficiently high. This is the principle which was utilized by early man in splitting of flints; Leakey referred to this process as "quartering"(7).

(2) If the chalk cylinder is now twisted in one's fingers, the principal tensile-stress trajectories can be traced as helices on the surface of the cylinder which make angles of 45° with the axis. If the twist is of sufficient magnitude fracture is initiated and without fail, will follow this helical surface, thus illustrating that fracture in glasseous materials occurs in a predictable way.

The foregoing examples are used to illustrate the formation of facture surfaces in non-crystalline materials, when the stress system is simple. In actual stone tool-making this is seldom the case, but qualitatively the foregoing principles still apply. Because of the somewhat more predictable nature we will restrict our discussion to pressure flaking.

If a spherical indenter is placed on a flat glass or rock surface, referred to as a platform, then principal tensile-stress trajectories will be formed which will diverge from the pressure point as shown in Figure 1. The solution of this problem was first given by Hertz(8) and the stress distribution in the material under an indenter results in what are often referred to as "Hertzian stresses". Thus, an indenter placed squarely on the surface, with a thrust normal to the surface, gives the typical conchoidal fracture observed with prehistoric flint forms. If the indenter is now placed at an angle to the platform, then the fracture surface will follow trajectory 3-4 of Figure 2b instead of the trajectory 1-2 of Figure 2a. This solution was obtained by Hamilton and Goodman(9) for the case of a normal thrust combined with surface friction of an indenter, which is equivalent to placing the indenter at an angle.

While it is possible to obtain solutions for more complicated situations in pressure flaking, the foregoing examples illustrate the fact that stone tool-making can be analyzed by present day knowledge of fracture of brittle materials.

Perforated Stone Disks.

As an example of engineering analysis applied to an archaeological artifact we will cite the following:

Centrally-perforated stone disks (Plate 1a) are found in some profusion in central California archaeological sites; other specimens are cited from Nevada(10), and Woodbury (10) shows one from Arizona. The California stone disks are generally considered as a trait of the Late Horizon, where they are associated with the common marker trait of clam shell disk beads(11). Woodbury, apparently having only a single example, by association included it among Pueblo III-IV, and suggested that it might be a diffusion from Mexico.

We have not concerned ourselves particularly with the question of how these disks were manufactured; water-worn pebbles of similar size and contour are found in some of the central Californian streams. The improvement of such stones would have required a minimum of work, although the question of the achievement of the centering of the perforation might well raise some thought. There has been no general agreement on the purpose of these perforated disks. Some of them are very well-finished, many of them approach very nearly perfect symmetry in diameter and in the centering of the perforation; their narrow range of size approaching standardization makes it appear that they were purposefully made.

Kroeber(12) reported on the use by the Valley Nisenan (Southern Maidu) of a perforated stone disk as a "spindle whorl" in connection with the spinning of some fiber from a tule-like plant, but did not describe the disk in any detail. The weight of those measured by us (average weight 80-100 grams) would seem disproportionate to the fibers in general use in central California (e.g. Apocynum, Asclepias, nettle, iris); at any rate, such use as a spindle whorl does not seem to have been reported from California by any other than the single Nisenan informant. The association with the appearance of clam shell disk beads, as well as those of steatite and magnesite, suggested to us that the stone disks might have been used as fly wheels for a pump drill. A search of the literature disclosed that at least several other investigators had made similar suggestions(13). Similar disks of whalebone have been used as fly wheels for pump drills in New Zealand(13).

It should be pointed out that there is no archaeological evidence for the precontact use of the pump drill in central California(14). Barrett(15) advanced his belief that it had reached the Pomo via the first Spanish settlers. There is no account that the Coast Indians' contact with Drake in 1579 may have introduced them to such a drilling device, but it certainly cannot be ruled out. Hawthorne and Smith(16) include reproductions of two plates (IV and V), engraved by Stephanus in 1576, showing two pump drills as part of the equipment of a 16th century goldsmith's shop and their translation of Theophilus indicates that it may have been in general use in the eleventh century in Europe. The ethnological specimens of pump drills in the Lowie Museum collection all have wooden fly wheels and three-sided files modified for drill bits, hence must be of post-contact manufacture.

Lacking either archaeological or ethnological evidence for the use of these perforated stone objects we decided to subject the problem to engineering analysis. Were these stone disks of a size and weight which would have rendered them feasible as fly wheels in drilling?

Let us look at a variety of drill drives (Figure 3). The bow drill (Figure 3a) still used by the Eskimo, has not been reported from central California. The shaft drill (Figure 3b) appears to have been universally used, probably because of its simplicity. The thigh drill (Figure 3c) has been observed in use by the California Indians in the 19th century (17); so, too, has the pump drill (Figure 3d). McGuire (17) devised a string or thong drill which he called a "top drill"; we independently arrived at a similar device (Figure 3e). It is not known to have been used in California, nor have we any data on the use of the twist drill (Figure 3f). It should be noted that, except for the twist drill, all drill drives require reversal of motion in their action.

The question then arises: which one of these drill drives could have been used effectively for the production of small perforations, if a disk such as one of these had been attached as a fly wheel to a shaft? A drill shaft set in rotary motion by any means whatever will tend to stop as soon as the driving torque is removed. This is due to the fact that the angular momentum of the drill is small and not much energy can be stored. The torque applied overcomes friction and drilling work, but cannot impart enough energy to the drill shaft to keep it in motion. Thus a steady torque must be applied during each portion of the cyclic motion. If a fly wheel is attached to the shaft then torque can be converted to stored energy in the fly wheel by virtue of its rotary motion. The higher the rotary speed the greater is the energy storage in the drill. This energy storage can be utilized in overcoming friction as well as unwinding and rewinding the strings of the drill.

If we now examine these suggested drills we can at once eliminate those for which the fly wheel is of no benefit but will in fact be a hindrance. Thus drills (Figures 3a-c) which may be called constant torque devices can be kept in motion without a fly wheel. Even if they had been attached to the shaft as weights, the operator would find that he must expend extra energy when setting the drill in motion and again when the direction is reversed because of the angular momentum which it would then possess. Whenever the rotational motion is altered, energy must be expended by supplying additional torque which would give no benefit to the operator. Consequently, our analysis shows that only the string drill (Figure 3e), the pump drill (Figure 3d) and the twist drill (Figure 3f) could be used effectively with a fly wheel, assuming that a stone-age man would have the intelligence to discover for himself that technique by which he might reap benefits in expenditures of energy. We conclude, from our analysis, supported by our own experiments, that if the perforated stone disks were used as fly wheels, then any of the drills shown in Figures 3d-f might have been known in early California.

Aboriginal Manufacture of Obsidian Ear Spools.

We would like to discuss a further instance of engineering analysis as applied to the possible method of manufacture of an artifact widely regarded as one of the outstanding products of preconquest Mexico. We refer to the obsidian ear spools (sometimes called ear plugs), examples of which have found their way into most important collections of pre-Columbian art. Descriptions have dwelt on their beauty, their fragility, their paper-thin walls, but almost never on the significance of the technical know-how implicit in their manufacture(18).

Figure 4 shows types of ear spools examined in the course of our investigation of museum specimens of the United States and Mexico. This list is not necessarily complete but gives enough variety of types to permit some generalization of a characteristic, namely, rotational symmetry, and it is this aspect which has been subjected to analysis. This property was possessed to a high degree by nearly all of the surfaces of the ear spools examined. As a consequence of this high rotational or axial symmetry the walls of either cylindrical or conical sections of the ear spools were uniform, often only approximately one millimeter thick and the outer and inner surfaces were concentric within a range of 0.025 millimeters.

The realization of this high axial symmetry has posed the problem of what manufacturing method could the ancient artisan have used to achieve this remarkable feat? While it is possible to think of sophisticated methods for generation of such surfaces, we are proposing a simple one which could have produced the seemingly precise surfaces of revolution in so brittle and fragile a material and which was within the capabilities of the precolumbian lapidary. No attempt was made to replicate a finished ear spool; only sufficient experimentation was carried out to demonstrate the workability of the proposed method(19).

In describing the method, which we have called the "Two string floating center method," we will assume that an ear plug blank has already been prepared with a central perforation by a variety of possible operations with which the aboriginal stone-worker was familiar. We will therefore focus our attention on the generation of the external conical or cylindrical surface such that the inner bore and the new external surface will be concentric. We assume that the bored blank is mounted on a mandrel of bamboo or wood and fixed thereto with an adhesive such as a pitched string around the shaft at the two ends, as shown in Figure 5. The rotation of the shaft can then be achieved by wrapping two suspended strings once or twice each around the ends of the shaft and placing a weight at the bottom. Figure 6 illustrates the way in which the operator could clutch the spindle through a lap and set it in rotary motion by moving his hand up and down. The split lap held in the operator's hand surrounds the perforated obsidian blank and is provided with abrasive for the material removal action. The lap could be of wood or of a metal such as copper. The lap need not be close-fitting but must be replaced during the operation as the diameter decreases. A possible alternate position, utilizing a back-strap device is shown in Figure 6b. If the driving effectiveness is not good enough with that shown in Figure 6a, improvement could be achieved by placing larger driving cylinders over the two ends of the shaft. This reduces the rotational speed for a given up-and-down movement but increases the torque for overcoming lapping resistance. Furthermore, if the string has a tendency to slip during the upward motion of the operator's hand because of the reduced torque, which is due to a well-known principle of mechanics, then a teeter-totter arrangement could be provided as shown in Figures 6c and 6d. The single weight is replaced by two equal weights. This permits the weights to be lifted alternately so that one is suspended in air while the other is touching the ground, assuring equal driving torque in both directions for the lapping movement. The idea of two suspended strings appropriately weighted down could have come from the weaving techniques known to have been practiced early by aboriginal peoples.

The second important feature of the suggested technique is that the process tends toward the production of concentricity through Newton's second law of motion, one of the important principles in dynamics. In simple terms, it states that a mass in motion (rectilinear or rotary) will persist in motion until acted upon by gravity or inertia forces. Applying this principle to the manufacture of ear spools, assuming a balanced mass system, we see that the ear spool and shaft, if rotating at, say, constant speed, would be acted upon by gravity forces and the operator's push as he moves the assembly up and down. The material removal on the outer surface of the spool would be uniform and there is high probability that initial concentricity will persist. However, if the center perforation of the spool is <u>not</u> initially concentric with the outer surface in contact with the lap, then a small but sufficient centripetal or radial force will be produced because of the unbalance of the rotating mass. It is assumed that both the rotating spool and the stationary lap have sufficient masses to cause such a force, which will tend to abrade the eccentric portion of the surface more rapidly than it does the other. The important feature is that the correcting process is self-terminating, once concentricity will have been achieved.

The authors tested the hypothesis experimentally. In order to be certain that the material used was similar to those suggested by early chroniclers to have been the raw materials of the native lapidary, obsidian was collected from outcroppings at Zinapécuaro, State of Michoacán, México. Cylindrical ear plug blanks were arbitrarily selected for experiment. They were prepared by facing a rough block of obsidian and removing specimen blanks by core drilling. Diamond saws and core drills were used to facilitate the process. The outside and inside diameters were respectively 26.6 millimeters and 12.7 millimeters, and a length of 50.8 millimeters. These dimensions have no significance and were chosen because of the availability of core drills. The center perforation for each blank was drilled eccentrically in order to test the hypothesis of automatic center correction during the process. The abrasive used was Boron carbide of 280 grid size. Several lap materials were used in the course of the investigation (cast iron, copper, wood).

Plate 1b shows a cylinder of obsidian in which the outside surface was lapped and reduced from a diameter of 26.6 millimeters to 20.32 millimeters at a rate of approximately 0.025 millimeters per minute. The experimental results lead us to the following conclusions:

1. The proposed method works satisfactorily for the production of cylindrical ear spools.
2. A copper split-shell type lap gave satisfactory accuracy without requiring a close fit of the lap.
3. Dimensional accuracies in diameter over a length of 50.8 millimeters of ± 0.05 millimeters and a roundness of ± 0.025 millimeters could be maintained without special precaution.
4. An improvement of concentricity of 10% was achieved for a reduction of approximately 10% in diameter. The masses to accomplish this result need not be large (i.e., a lap of one-or two-pound weight at rotary speeds of approximately 10 rev./sec.) When large reductions in diameter are required, several laps should be used in order to improve or maintain concentricity.

In closing we feel it incumbent to raise the question: is information of this sort really useful to the archaeologist? Would McGuire's painstaking contribution to technology have been enhanced had he known that the silica group of stones is isotropic? Certainly precolumbian lapidaries produced consummate examples of art with no knowledge of "Hertzian stresses" or Newton's Laws of Motion. We feel that there is a practical application for lithomechanic studies such as these: sometimes their best function may be in the elimination of what are only seductive speculations. At any rate, the age of the Renaissance Man is past, and we are living in an era where the proliferation of data exceeds our ability to absorb it. The answer would seem to lie in an exchange of the special knowledge developed in all disciplines.

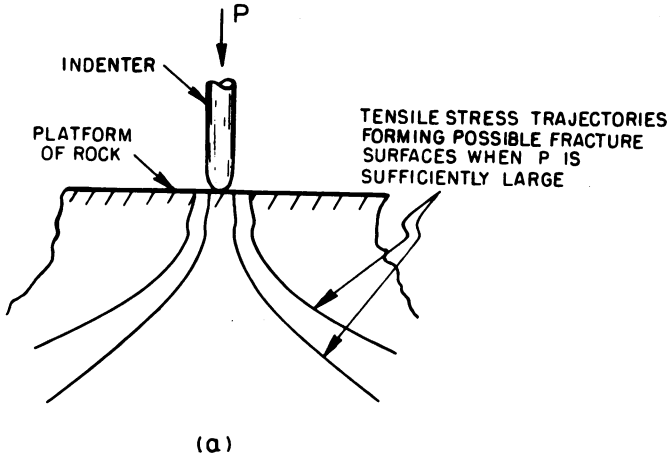
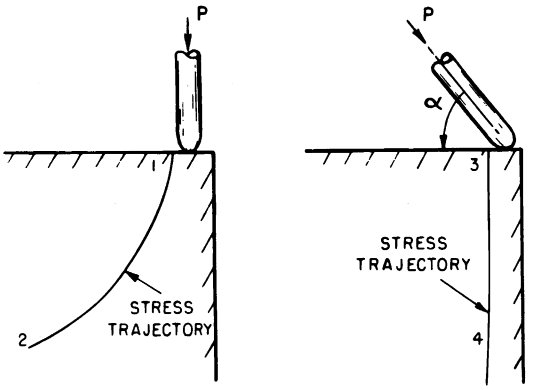


FIGURE I TENSILE-STRESS TRAJECTORIES INDUCED BY A BALL INDENTER UNDER LOAD P PRESSING ON A FLAT SURFACE



(a) NORMAL LOAD (b) LOAD AT ANGLE α

FIGURE 2 DEPENDENCE OF DIRECTION OF TENSILE-STRESS TRAJECTORIES ON DIRECTION OF LOAD

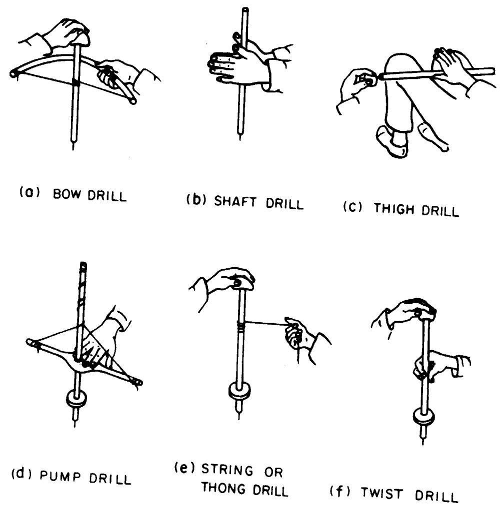


Fig. 3. Various Drill Drives

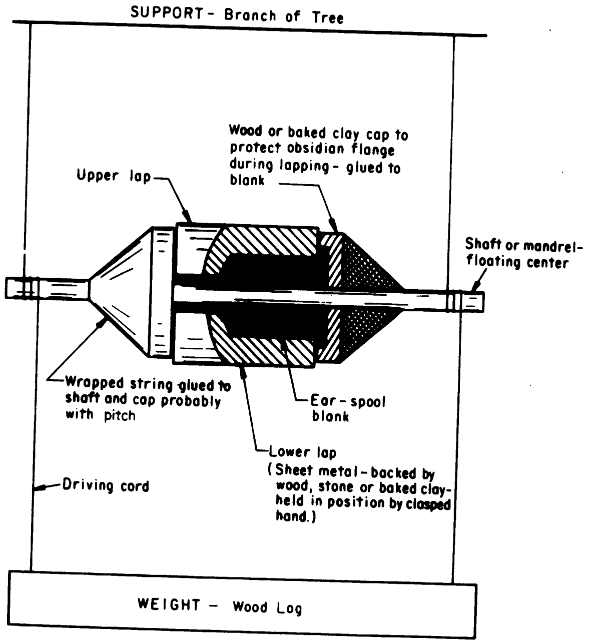
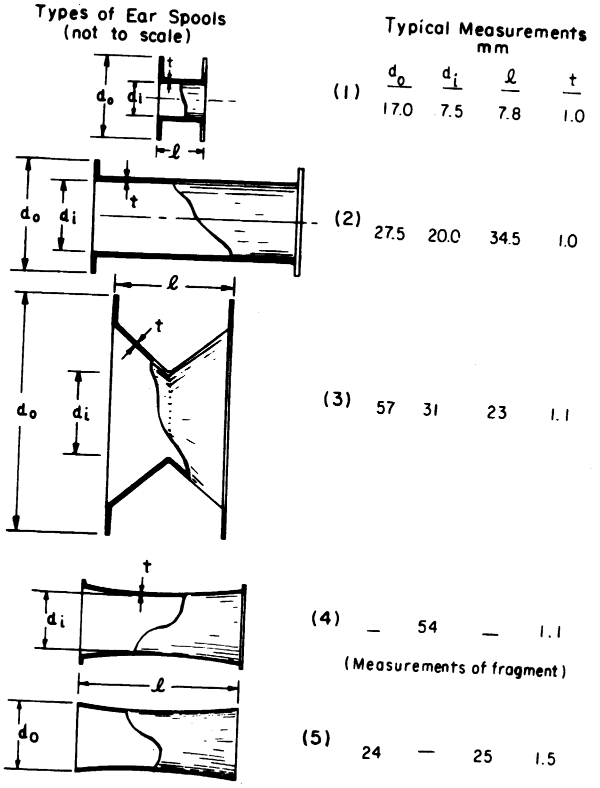


Fig. 5. Lapping Assembly



Typical Measurements mm

	d_o	d_i	ℓ	t
(1)	17.0	7.5	7.8	1.0
(2)	27.5	20.0	34.5	1.0
(3)	57	31	23	1.1
(4)	—	54	—	1.1
(5)	24	—	25	1.5

(Measurements of fragment)

Fig. 4. Types of Ear Spools

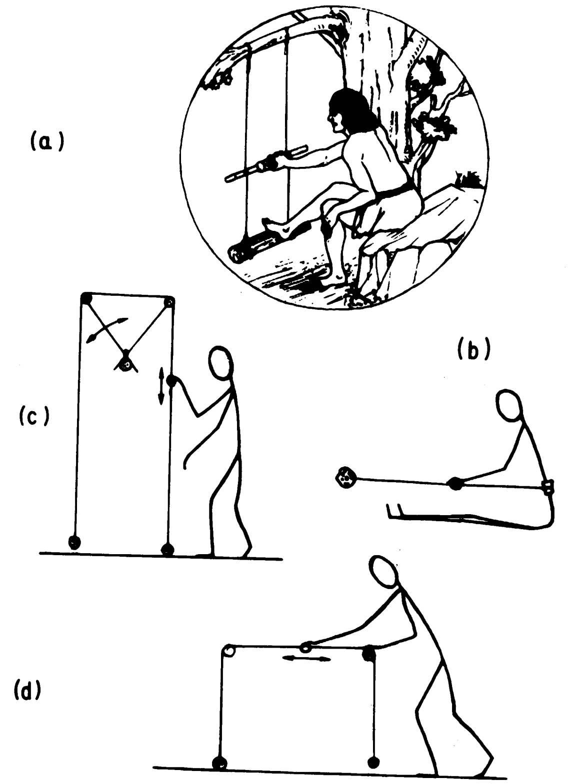


Fig. 6. Two-String Floating-Center Drives

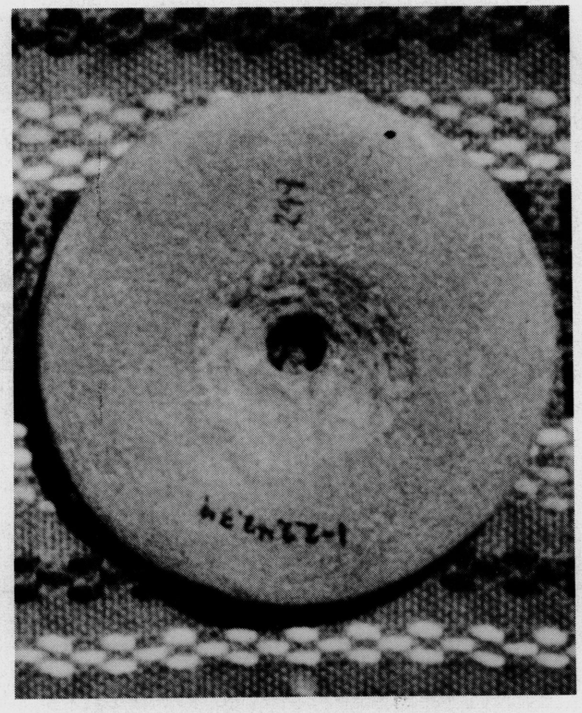


Plate 1a. Perforated Stone Disk (Specimen No. 1-224234, Lowie Museum, University of California, Berkeley.) Site: CCo-138. Dimensions: Diameter 7.5 cm, Diameter of pecked area, 3.5 cm, Diameter of perforation (biconical) .7 cm, Weight: 103.2 grams. Material: Fine-grained sandstone.

Plate 1b. Obsidian Blank and Lapped Specimen Produced by the Two-String Floating-Center Method

References and Notes

1. L. W. Alvarez, J. A. Anderson, F. El Bedwei, J. Burkhard, A. Fakhry, A. Girgis, A. Goneid, F. Hassan, D. Iverson, G. Lynch, Z. Miligy, A. H. Moussa, M. Sharkawi, L. Yazolino, Science 167,832 (1970).

2. J. O. Outwater, Jr., Amer. Antiquity 22,258(1957).

3. C. Rau, Smithsonian Inst. Ann. Rep. 1868,1(1869); Amer. Naturalist 15, 536(1881); J. D. McGuire, Amer. Anthropologist 5,165(1892); U.S. Nat'l Mus. Rep.(1896).

4. R. F. Heizer and J. A. Graham,(1970) (In press).

5. S. A. Semenov, Prehistoric Technology, M. W. Thompson, Trans.(Barnes and Noble, New York, 1964); D. E. Crabtree, Amer. Antiquity 33,446(1968); E. N. Wilmsen, Science 161,982(1968).

6. S. Vaidyanathan, Dissertation, Dep't Engineering, University of California, Berkeley(1970).

7. K. P. Oakley, Man the Tool-Maker, London,5th ed.,(1965); L. S. B. Leakey, Adam's Ancestors, Harper & Row, New York 4th ed.,(1960).

8. H. Hertz, Journ.f.d.reine u.angewandte Mathematik,91,156,Berlin(1881); Verhandl.d.Vereins Beförderung d.Gewerbefleisses,61,449,Berlin(1882); Gesammelte Werke,1,185,Fig.19,Barth,Leipzig(1895); Miscellaneous Papers,163,MacMillan,London(1896).

9. G. M. Hamilton and L. E. Goodman,Trans.A.S.M.E. Journ.App.Mech.33, Series E,371(1966).

10. M. R. Harrington,Indian Notes, Mus. of Amer. Indian,4,40(1927); L. L. Loud and M. R. Harrington, U.C.P.A.A.E.25,viii ff.,U.C.Press, Berkeley(1929); R. B. Woodbury, Rep.6,Awatovi Expedition,Peabody Papers, 34,185,Cambridge,Mass.,(1954).

11. H. C. Meredith,Prehistoric Implements,276
W. E. Schenck and E. J. Dawson,U.C.P.A.A.E. 25,385,U.C. Press, Berkeley (1929); R. F. Heizer and F. Fenenga,Amer.Anthropologist,N.S.41,378(1939); J. B. Lillard, R. F. Heizer and F. Fenenga,Bull.2,Sacramento Jun.Coll., (1939); R. K. Beardsley,Amer.Antiquity 14,1(1948); U.C.Arch.Survey Rep. 24,5-7(1954),U.C.Press, Berkeley.

12. A. L. Kroeber,U.C.P.A.A.E. 24,252, University of California Press, Berkeley(1929); Handbook of the Indians of California,Bull.78, Bur. Amer. Eth.Smithsonian Inst.Washington(1925)(Reprinted 1953).

13. Sir J. Evans,The Ancient Stone Implements,Weapons and Ornaments of Great Britain,14,2nd ed.London and Bombay(1897); J. D. McGuire,A Study of the Primitive Methods of Drilling,U.S.Nat'l Mus.Rep.,1893-4,656,Fig.46, Washington(1896); F. B. Chapman,Trans. and Proc. New Zealand Inst.24,N.S.,479 ff.Wellington(1892).

14. W. H. Holmes, Handbook of Aboriginal American Antiquities, Part I,Bull.60, B.A.E.,Smithsonian Inst.,350(1919); K. Birket-Smith,The Caribou Eskimos, Part II,97,Copenhagen(1929).

15. S. A. Barrett,Material Aspects of Pomo Culture,PartII,Bull. of Pub.Mus. of Milwaukee,20,261,308(1952).

16. J. G. Hawthorne and C. S. Smith,On Divers Arts,The Treatise of Theophilus, Trans. from Med.Latin,University of Chicago Press(1963).

17. S. A. Barrett,Material Aspects of Pomo Culture,Part II,Bull. of Pub.Mus. of Milwaukee,20,285,Plates 47,48(1952); J. W. Hudson, Overland Monthly, 30,101 ff., and Plate,San Francisco(1897); J. D. McGuire,U.S.Nat'l Mus. Rep.1893-94,718,Fig. 143, Washington(1896).

18. L. E. Mirambell, Tecnicas Lapidarias Prehispanicas, Investigaciones 14, Insto.Nac. de Antrop.e Hist., Mexico(1968).

19. E. G. Thomsen and Harriette H. Thomsen, Precolumbian Ear Spools: An Investigation of Possible Manufacturing Methods,(in press). (Contributions of the University of California Archaeological Research Facility, University of California Department of Anthropology, Berkeley,1970).