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The origin of two purportedly pre-Columbian Mexican crystal skulls

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Abstract

The well-known life-size rock crystal skull in the British Museum was purchased in 1897 as an example of genuine pre-Columbian workmanship, but its authenticity has been the subject of increasing speculation since the 1930s. This paper is concerned with the history, technology and material of the skull and another larger white quartz skull, donated recently to the Smithsonian Institution. Manufacturing techniques were investigated, using scanning electron microscopy to examine tool marks on the artefacts, and compared with Mesoamerican material from secure contexts. A Mixtec rock crystal goblet and a group of Aztec/Mixtec rock crystal beads show no evidence of lapidary wheels. They were probably worked with stone and wood tools charged with abrasives, some of which may have been as hard as corundum. Textual evidence for Mexican lapidary techniques during the early colonial period, supported by limited archaeological evidence, also indicates a technology without the wheel, probably based on natural tool materials. In contrast, the two skulls under consideration were carved with rotary wheels. The British Museum skull was worked with hard abrasives such as corundum or diamond, whereas X-ray diffraction revealed traces of carborundum (SiC), a hard modern synthetic abrasive, on the Smithsonian skull. Investigation of fluid and solid inclusions in the quartz of the British Museum skull, using microscopy and Raman spectroscopy, shows that the material formed in a mesothermal metamorphic environment equivalent to greenschist facies. This suggests that the quartz was obtained from Brazil or Madagascar, areas far outside pre-Columbian trade networks. Recent archival research revealed that the British Museum skull was rejected as a modern artefact by the Museo Nacional de Mexico in 1885, when offered for sale by the collector and dealer, Eugène Boban. These findings lead to the conclusion that the British Museum skull was worked in Europe during the nineteenth century. The Smithsonian Institution skull was probably manufactured shortly before it was bought in Mexico City in 1960; large blocks of white quartz would have been available from deposits in Mexico and the U.S.A.

Key words: OPTICAL MICROSCOPY, SCANNING ELECTRON MICROSCOPY, RAMAN SPECTROSCOPY, X-RAY DIFFRACTION, LAPIDARY TECHNOLOGY, TOOL MARK, PROVENANCE, FLUID INCLUSION, QUARTZ, CRYSTAL SKULL, MEXICO, PRE-COLUMBIAN PERIOD, AUTHENTICITY

Introduction

The authenticity of archaeological artefacts in museum collections is of crucial importance, as incorrectly attributed objects can distort our understanding of the past, particularly for the general public, who may not possess the critical awareness of professional specialists. Few artefacts illustrate this better than the so-called crystal skulls, which have become the subject of numerous popular books, articles and documentary films since the twentieth century. The two best-known examples of these artefacts are in the collections of the British Museum, London, and the Musée du Quai Branly, Paris, and the present study concerns the investigation of the former, and a skull from the Smithsonian Institution, Washington, D.C.

The life-sized carving of a human skull made from a single block of rock crystal in the British Museum was purchased from Tiffany and Company, Union Square, New York, in November 1897 (1898-1, Fig. 1a). It is apparent from documents in the Museum's archives that earlier in the month George Frederick Kunz, Vice President of Tiffany's, had written to (Sir) Charles Hercules Read, Keeper of the Department of British & Mediaeval Antiquities & Ethnography at the Museum, recommending the purchase of the skull. Kunz, a mineralogist of considerable standing, continued '*I would feel much pleased to have your institution possess this remarkable object which you will find fully* *described in Gems and Precious Stones of North America p.285-286 1890 by George F Kunz'*. It was stated in this publication that the skull '*was brought from Mexico by a Spanish officer sometime before the French occupation of Mexico, and was sold to an English collector, at whose death it passed into the hands of E. Boban, of Paris, and then became the property of Mr. Sisson'*. The author admitted '*Little is known of its history and nothing of its origin'* and quoted the opinion of others that the skull was of ancient Mexican origin. Human skulls worn as ornaments and displayed on racks were known to have featured in Aztec art and iconography in Mexico at the time of first contact with the Spanish in AD 1519 (Carmichael, 1970, p. 12; McEwan et al., forthcoming). In the early twentieth century, the crystal skull was displayed alongside genuine objects.

Since its acquisition, the skull has attracted extraordinary attention from both the public and academics. The spectacular appearances of this large carving of clear quartz and others in private and museum collections continue to exercise particular fascination. An early study was concerned with the morphological comparison of the British Museum skull and another life-sized rock crystal skull in private ownership, and led to speculation on their origin (Morant, 1936). Increasing doubts were cast on the authenticity of the British Museum carving. Although Kunz (1890) suggested that the rock crystal may have been obtained from a source in Mexico or California, the large size of the piece came to be regarded as unusual for pre-Columbian lapidary carvings, which were typically worked from relatively small, water worn pebbles collected from alluvial deposits. The Museum consulted the geologist, Ernest Brown, who in response to demand for quartz crystals for use as electrical oscillator plates, had worked in Brazil from 1944 to 1948 (Brown, 1950). Brown considered that the quartz for the skull originated from the Brazilian massif, where large crystals occur in immense quantities. The trade network of the Aztecs extended into North America but there is no evidence for trade with Brazil. Furthermore, the Brazilian sources were not exploited until the nineteenth century.

Suspicions also arose over the lapidary technology employed to work the skull. During the 1960s, an investigation of carving techniques on the skull was undertaken by the Research Laboratory at the British Museum. Observations made with a binocular microscope suggested the teeth were engraved with a rotary disc-shaped tool (or wheel), thought to have been unavailable in pre-Columbian Mesoamerica (Maguire, 1894; Holmes, 1919; Kidder et al., 1946; Drucker, 1955; Foshag, 1957). However, the possibility that the teeth could have been wheel-cut sometime after the original carving was also recognised. The results reinforced doubts about the ancient origin of the skull. They were summarized by Mark Jones et al. (1990, pp. 296-7) in the exhibition catalogue *Fake? The Art of Deception* under the heading *The limits of expertise,* as at that time it was felt that a definitive conclusion as to the origin of the skull was not possible.

Despite the reality that no quartz skulls have to date been retrieved from well-documented official archaeological excavations, an increasing number of quartz skulls in a range of sizes have become known during the past century. In 1992, a particularly large white (or milky) quartz skull with a hollow cranium (# 409954, Fig. 2a) was sent to the Smithsonian Institution, with minimal documentation indicating the artefact had been purchased in Mexico City in 1960. The arrival of the skull highlighted the curatorial dilemmas created by objects of dubious authenticity and led to a study of archival documents concerned with the early history and acquisition of crystal skulls in various museum collections. It became apparent that not only had the dealer, Eugène Boban, owned the British Museum skull (as alluded to above), he had previously also been involved in the sale of three other rock crystal skulls, one *c.* 11 cm high and two small ones (less than 5 cm high), currently in the Musée du Quai Branly, Paris (Walsh, 1997; 2006). The quartz skulls appear to be stylistically somewhat anomalous when compared with ancient Mesoamerican depictions. For example on all five skulls, the rigid linearity of features representing teeth or gaps between teeth (in this study, these linear features are simply termed *teeth*) contrasts with the more precise execution of teeth on pre-Columbian carvings, such as the skull worn by the Aztec moon goddess to be seen on the Coyolxauqui stone (Museo del Templo Mayor, Mexico City).

In view of the potential importance of these quartz skulls for the interpretation of Mesoamerican archaeology, coupled with the great public interest in these putative artefacts and the healing qualities and mystical powers sometimes attributed to them, a collaborative programme of research into the lapidary technology, the history and the provenance of the quartz was set up. The origin of the two large crystal skulls, one in the

British Museum and the other in the Smithsonian Institution, is discussed in the present paper.

2. Methods of examination

2.1. Carved features

The fine detail preserved on the carved features of hard stone artefacts is ideal for the study of ancient lapidary technology. The use of tools and techniques can usually be recognised from the characteristic morphology of the 'tool marks' of carved features. The present investigation was based on the approach originally developed by Sax and Meeks (1995; Sax et al., 2000) for the recognition of methods of engraving on quartz cylinder seals from the ancient Middle East, and subsequently adapted for the analysis of lapidary work on jade (Sax et al., 2004). Following an initial survey of the skulls using optical microscopy at magnifications up to x60, features apparently bearing evidence for carving technique were selected for more detailed examination by scanning electron microscopy (SEM: JEOL JSM 840). Detailed impressions of features of interest were made with silicone moulding material, and coated with a thin layer of gold. The method of moulding facilitates examination of deeper features, where important evidence for carving technique is often preserved. To identify techniques of carving, moulds of the carved features on the skulls were compared with moulded standard features produced experimentally on quartz using a range of non-rotary and rotary techniques, tools and abrasive materials (Sax et al., 1998). The mineralogical compositions of minute deposits, possibly abrasives, on the skulls were sampled and analysed by X-ray diffraction using Debye-Scherrer cameras (XRD).

For comparison, the lapidary practices of pre-Columbian Mesoamerica were evaluated in three ways. First, the relatively limited archaeological evidence for workshops, tools, tool materials and raw materials was surveyed. Secondly, consideration was given to the pictorial and textual evidence of Aztec and Mixtec histories in Codices, in particular, the *Florentine Codex* documented by the Franciscan Fray Bernardino de Sahagún in the early colonial period. Thirdly, optical and SEM microscopy was used to examine artefacts from well-documented pre-Columbian contexts in Mexico: a Mixtec rock crystal goblet (10.105605 Museo de las Culturas de Oaxaca, Fig. 3), and a group of Aztec/Mixtec rock crystal beads (39/17/3258 10 251289 3/13, -4/13, -7/13; 39/55/3300 10 251289 13/13; 39/63/3306 10 251289 1/13 Museo del Templo Mayor, Mexico City). To complement this, consideration was also given to a group of Mayan jadeite/greenstone artefacts from Pomona, currently in the British Museum, and 40 or so Olmec jadeite and quartz artefacts from La Venta, Tres Zapotes and Las Tuxtlas, currently in the Smithsonian Institution.

2.2. Inclusions in quartz

The fine detail and composition of inclusions commonly found in rock crystal or other rocks and minerals formed or recrystallised in the presence of fluid phases may indicate the geological environment and conditions under which the original crystal formed, permitting suggestions on the provenance of the source (Roedder, 1962, 1984; Rankin 2005). Inclusions initially detected in the skulls using a x10 lens were recorded using a high resolution micro-camera equipped with a series of high-powered lenses up to x200 magnification. The experimental set-up allowed considerable depth of focus at intermediate magnifications. More detailed studies were also carried out on selected, well developed fluid and solid inclusions in the British Museum crystal, using a Leica MZ APO binocular microscope fitted with a high resolution digital camera and a Leica Montage package which allowed images to be recorded at magnifications up to x100 with exceptional depth of focus.

In addition, a small sample of a green solid inclusion cluster exposed at the surface of the British Museum crystal was carefully extracted for examination by SEM equipped with an energy dispersive x-ray analyser (EDX). Semi-quantitative EDX data were obtained for elements that were significantly above background levels. The sample was then analysed by Raman spectroscopy, using a Dilor Infinity Instrument equipped with a 532 nm laser.

3. Pre-Columbian lapidary technology

3.1. Historical and archaeological evidence

As noted above, a number of early studies suggested that traditional pre-Columbian lapidary methods were relatively simple by modern standards. More recent work has confirmed these findings and is summarised by Walsh (in press a). All these studies were concerned with artefacts dating to the Maya culture of the Classic period, *c.* 200 BC-AD 900, or the Olmec culture of the Preclassic or formative period, *c.* 1200-400 BC. Pasztory (1983, p. 250) commented that '*Aztec lapidary art has never been studied in detail'*. The parallel lack of evidence for lapidary practices during the Aztec and Mixtec cultures of the post-Classic period, *c.* AD 1200-1519, is ameliorated to some extent by information in Codices on indigenous technologies in the early colonial period. At this time, it is unlikely that pre-Colonial technologies had been significantly modified.

The Aztec methods were documented by Sahagún (Book 9, Part II) between 1575 and 1577 in the Nahuatl language of his informants and Spanish. Lapidaries were apparently well acquainted with the physical properties of a wide range of stones. The working of the hardest stones, such as rock crystal and amethyst, was the preserve of master lapidaries. Sahagún stated that '*a piece of metal'* was initially used to shatter amethyst crystals then shape selected

pieces to size. In West Mexico between *c.* AD 1250 and first contact with the Spanish in 1519, metal tools, harder than earlier copper tools, were fashioned by cold working (or hot working) various copper alloys cast as ingots or blanks (Hosler, 1994, pp. 126-169); however, none of these tools appear to have been intended or used as implements for lapidary working. The use of metal tools in lapidary workshops may have been introduced after 1519. Carving experiments (Sax et al., 1998) showed that rock crystal and amethyst may be relatively easily shaped by pecking/flaking techniques with pointed stone or copper-based tools. In addition, Aztec lapidaries used small rigid saws. A painting (Fig. 4) from the *Codex Mendoza*, compiled between 1541and 1542, shows an artisan apparently using a stone (possibly flint) tool to saw individual jade/green stone beads from a pre-formed tube. In a second stage of working, Sahagún recorded that abrasives were applied to smooth the shaped surfaces. This was a lengthy process and the ultimate aim was to provide a gleaming polish with wood polishers. Bamboo polishers (which contain natural opaline silica), flint and other stone tools and also drills were used by master lapidaries.

Interpretation of the Nahuatl language is particularly problematic regarding the composition of lapidary abrasive sands (Sahagún, Book 11, Part X11). The term *emery* appears to have been used generically to describe variously coloured sands; *flint emery* referred specifically to ground flint. Emery is an impure microcrystalline variety of the mineral corundum (aluminium oxide), which has a Mohs' scale hardness, H, of 9.

However, the mineralogist, Foshag (1957, p. 50), considered that the use of abrasives, such as emery, that are considerably harder than quartz (H=7) or jadeite (H=6.5) was unlikely in pre-Columbian times.

No evidence for lapidary rotary wheels has been found in ancient Mesoamerica. In contrast to drills, which may be hand-held, for example over a capstone and bow-driven (Di Castro, 1997, pp. 153-160), the use of wheels would have been dependent on devices similar in function to lathes. The attachment of a wheel to a spindle (or axle) fixed between bearings allows the tool to be rotated by some means. Although the possibility that wheeled vehicles may have been used in the low lying coastal region of Eastern Mexico during the late Classic period was raised by the excavation of four four-legged ceramic animal toys and twelve perforated clay discs from the same trench at Tres Zapotes, Veracruz (Drucker, 1943, p. 112, pl. 49), neither vehicular nor pottery wheels were known to Aztecs and Mixtec artesans.

The evidence discussed above suggests that, during the post-Classic period, hard stones were worked by a combination of methods that included enlarging natural fractures, percussion/pecking, sawing/filing, incising/scraping and drilling. Tools were hand-held and made of organic materials, such as wood, or stones typically no harder than quartz; metal tools were possibly a post-Columbian introduction. Relatively soft abrasives are thought to have been used. These inferences may be compared with the evidence found on the quartz goblet and beads.

3.2. Observations on a goblet, Mixtec culture

The goblet (Fig. 3a) is 8.8 cm high, the largest documented rock crystal artefact to have been excavated at a pre-Columbian site. It was recovered from tomb 7, a Zapotec tomb reused by Mixtecs in post-Classic times, *c*. AD 900-1521, at Monte Albán, Oaxaca (Caso, 1969). Observation with a binocular microscope showed that a high density of tool marks is preserved on the goblet. No tool marks appear to relate to the initial stages of shaping. The fine detail of all those remaining provides evidence for the methods used to smooth and polish the goblet.

The tool marks on external surfaces are similar to most of those on internal surfaces. A mould showing details of the tool marks is seen in the SEM micrograph, Figure 3b: single linear striations occur in random orientations. These irregular characteristics are consistent with a non-rotary technique of carving, involving the application of straight files in random directions. Files with shorter working edges would also have been necessary for working the internal surfaces of the artefact; the ends of straight files or files specially shaped with curved working edges, similar to modern riffler files, would have been suitable. The notable, soft shaping of this pre-Columbian artefact is consistent with a relatively soft tool material, such as 'hard' wood (Sax et al., 1998, p. 9, Fig. 3f).

Although it seems likely that tools were occasionally rotated, no clear evidence for drilling was found. Tool marks on the internal surfaces of the cup and the base are occasionally curved but none are circumferential, providing no support for the suggestion of Langenscheidt (2006) that the goblet was ground with pressure and a rotating movement.

The variable cross-sectional thickness of the tool marks appears to reflect the use of abrasive particles of different grain sizes, suggesting that increasingly fine abrasives were applied to the surfaces for smoothing, prior to polishing; alternatively, the abrasives may have been poorly-sorted and a single abrasive may have had variable grain size. Comparison of the tool marks on the goblet with those of experimental carvings made on rock crystal using files separately charged with abrasives of different hardness also suggests that the numerous linear tool marks on the goblet were made with an abrasive harder than quartz, such as almandine garnet (H=7-7.5) or emery/corundum (H=9) (compare Sax et al., 1998, pp. 8-9, Figs. 3-4). The experimental use of quartz sand produced occasional coarse, often non-linear striations, and continued filing gave shorter finer linear striations, unlike those on the goblet. Our observations provide some support for Langenscheidt (2006), who speculated that corundum sand was employed; it seems unlikely however that the abrasive was diamond. Durán, the sixteenth century priest, recorded that during the rule of Motecuhzoma, 1502-1520, the Aztecs obtained lapidary sands from the Mixtec provinces of Quetzaltepec and Tototeec, now in Oaxaca. Although the mineralogy of these sands is not known, sources of almandine garnet are found at San Sebastián Abasolo, Oaxaca (Panczner, 1987), and sources of emery and/or corundum occur in Oaxaca and neighbouring Guerrero and Puebla (Langenscheidt, 2006).

The tool marks protrude upwards on the mould (Fig. 3b): they are recessed in the goblet. They also have rough and unpolished surfaces, which contrast with the remaining smooth and highly polished surfaces of the goblet. The combination of the two textures gives the artefact a softly-polished overall appearance. Furthermore, unpolished recesses are diagnostic of rigid polishing tools, such as the wood and cane polishers described by Sahagún (Foshag 1957, pp. 55-56; Chenault 1986, pp. 61-62). Unlike soft felt or leather-covered tools applied with fine-grained polishing mixes in post-Columbian times, rigid polishers would not have reached recessed surfaces.

3.3. Observations on five beads, Aztec/Mixtec culture

The five rock crystal beads excavated at the Aztec site of Templo Mayor, Mexico City, AD 1325-1519 (López Luján, 1994, p. 341) are subspherical, *c.* 12 mm long and *c.* 16 mm maximum diameter. The examination of the beads was limited by their poor state of preservation. They have crazed and fractured surfaces and appeared to have been subjected to strong heating, possibly in a fire at the time of burial. To avoid any risk of further damage, the beads were not moulded. Additional difficulties were caused by coatings of varnish, presumably applied recently, that mask most details of the tool marks. However, observation by binocular microscopy allows some interpretation of the method of perforation.

The perforations, apparent through the sides of the beads, have pronounced biconical profiles, indicating that the opposite ends of each bead were drilled to meet near the centre. The profiles are consistent with the use of solid drills with relatively broad, tapering heads. Several minute areas (*c.* 1-2 mm square) of the perforations remain unvarnished. An area on bead 13/13 has a rough surface texture with apparently circumferential, uneven coarse striations. Previous experiments showed that conical profiles and similar surface textures are produced on rock crystal with drills made of a tough stone, such as flint/chert, used with or without an abrasive of similar hardness to quartz (Sax et al., 1998, p. 18).

In contrast, apparently circumferential, regular fine striations are present on another unvarnished area of this perforation and those of beads 3/13 and 4/13. These characteristics suggest that a fine abrasive harder than quartz was then used, possibly with a wood drill, to smooth the surfaces of the perforations.

Investigation of the quartz goblet and beads provides supportive evidence for the Codices, confirming the practice of relatively simple lapidary technology during the post-Classic period. No evidence for lathe-mounted rotary wheels or metal tools was found. The carving of the two skulls (below) may be judged against these results.

4. Lapidary technology: the skulls

4.1. British Museum skull

In contrast to the surfaces of the goblet (Fig. 3a), almost all those of the skull, with the main exception of the teeth, have a high polish (Fig. 1a). Also, unlike the soft shaping of the goblet, the carved features of the skull are sharply defined (Fig. 1b). Observation with a binocular microscope shows that traces of tool marks are preserved. The macro characteristics of the carved features and SEM observation of the fine detail of the tool marks provides evidence for the methods used to finely shape, smooth and engrave the skull.

Simple straight features represent the teeth (see terminology in **Introduction**) and a long straight feature resembling the ‘mouth’ defines the space between the upper and lower teeth. These features are deeply engraved and their carving is considered first. A mould of details of the features is shown in the SEM micrograph, Figure 1c; in this oblique annotated view of the mould, the engraved features protrude upwards. The end of the mouth is seen across the image between an upper tooth and a lower tooth. Two stages of working are apparent on the teeth. Prior to polishing, the teeth were carved as relatively broad shallow features (*c*. 2 mm wide as indicated by the dotted line across the lower tooth (Fig. 1c). In a second stage of working, each tooth was emphasized by the cutting of a deeper narrower feature (0.3-1.5 mm wide); these have unpolished surfaces and were clearly worked subsequent to polishing. The possibility that the teeth were re-cut at a later date cannot be ruled out. The mouth was apparently engraved deeply in a single stage prior to polishing.

Further observation of the engraved features indicates that rotary wheels were used for both stages of engraving. On the mould (Fig. 1c), the cuts along the narrow parts of the teeth are convex (as indicated along the upper tooth); similarly, the cut along the end of the mouth is convex. The convex curvature reflects the concave depth of these features in the skull. Regular parallel striations are present along the surfaces of these features, for example, on the lower tooth. Features with regular curvilinear characteristics like those of the teeth and the mouth were produced experimentally on quartz using metal wheels charged with a loose abrasive mix (Sax et al., 1998, pp. 7-8, 19, Fig. 6c). The quartz was hand-held and moved against the rim of a rotating wheel, mounted on an electrically-driven lathe.

The remaining surfaces of the skull were not entirely smoothed prior to polishing, and traces of tool marks are preserved within the polish. Foshag (1957, p. 51) referred to similar marks on pre-Columbian artefacts as *'ghosts'* of the technique. Those on the skull are characteristic of rotary tools.

Evidence for the use of drills was found. A circular hole preserved in the base of the proper right nasal cavity indicates that drills were employed for shaping these features. Circumferential striations around the sides of the eye sockets are also consistent with drilling. In contrast, longitudinal parallel striations are preserved in the polished surfaces of the remaining recessed features, for example, the more or less oviform recess forming a *temporal fossa*, *c*. 6 cm by *c*. 3 cm, either side of the cranium (Fig. 1b). Convex curvature along a mould reflects the concave depth of the *temporal fossae* in the skull; regular linear parallel striations are preserved in the polished surfaces (Fig. 1d**).** These characteristics are consistent with the use of a rotary wheel, 1 cm or more thick, and an abrasive. Likewise, a recessed circular feature (*c*. 3 cm diameter) representing the *foramen magnum* under the cranium and surfaces hollowed out behind the jaw were wheel-cut. Furthermore, the extension of similar parallel striations over flattish parts of the base (Fig. 1e) and the convex surface of a small unpolished patch, *c*. 1 cm by 0.5 cm, above the proper right optical socket towards the nasal socket indicate that rotary wheel-cutting, rather than filing, was also used to work the flat and convex surfaces of the skull. Supportive evidence for the extensive use of wheel-cutting is present around minute pits in the rock crystal surface. Several pits protrude upwards on the mould in Figure 1e: drag marks made by the abrasive to right hand side of each pit reflect the use of a high speed cutting action.

The cross-sectional thickness of the striations varies in different parts of the skull: the striations are finer on the *temporal fossae* (Fig. 1d) than the base (Fig. 1e). These variations reflect the use of a coarse abrasive for grinding surfaces then increasingly fine abrasives for smoothing the upper surfaces of the skull. The use of an abrasive considerably harder than quartz, such as diamond (H=10) or emery/corundum (H=9), applied with hard, iron or steel tools, is inferred from the sharp definition of the carved features (Fig. 1b; Sax et al., 1998, p. 18).

4.2. Smithsonian skull

Numerous natural cavities in the white quartz material of the Smithsonian skull (Fig. 2a) render it translucent with a cloudy appearance; they probably precluded the effective application of a high polish. Instead, a matt finish extends over more or less all the external surfaces and the internal surfaces of the hollow cranium. Although only faint traces of tool marks remain, their characteristics nevertheless provide evidence for the techniques used to finely shape, smooth and engrave the skull. The identification of abrasive particles trapped in the surface allows further description of the particular lapidary method.

The engraved features forming the teeth and the mouth have similar characteristics to those worked on the British Museum skull. In the oblique view of a mould showing one end of the mouth and details of two teeth in the Smithsonian skull (Fig. 2b), the convex profiles along the features are comparable with those of the wheel-cut features on the British Museum skull (Fig. 1c). The teeth on the Smithsonian skull however have a matt finish and were worked prior to the finishing process.

Extensive use was also made of wheel-cutting for shaping and smoothing the convex external surface and the concave internal surface of the cranium. The characteristics of the tool marks on these surfaces are similar but they occur more frequently on the internal surface, where working access is restricted by the hole in the base. Two types of tool marks are present: groups of fine parallel striations and coarser single striations. Figure 2c, a mould of the internal surface, shows a small area (*c*. 4 mm by 3 mm) remaining untreated by the finishing process: particularly fine, closely spaced, parallel striations lie across the image. As discussed above, the striations are likely to have been produced using an abrasive of fine grain size for a final stage of smoothing. Similar but coarser parallel striations also occur on the skull, reflecting the earlier use of coarser abrasives. These striations may be linear or slightly curved. The presence of curvilinear striations on the external surface indicates that the abrasives were used with rotary wheels or pads, rather than non-rotary straight files that produce linear striations.

The second type of tool mark comprises single coarse striations (arrowed in Fig. 2c) which can extend the full length of 2.5 cm moulds and, like the parallel striations, are curvilinear and occur in random orientations. These may reflect the use of an abrasive of uneven grain size or grinding wheels that were '*improperly dressed'* (Sinkankas, 1984, pp. 47-48). For instance, single striations may be produced by sharply-shaped edges of wheels held obliquely to the surface being worked.

A minute black and red deposit preserved in a cavity of the quartz was identified by XRD as silicon carbide. The natural occurrence of this mineral is very rare and virtually confined to meteorites. The compound was first synthesized at the end of the nineteenth century AD. With a hardness, H of 9.5, approaching that of diamond (H=10), it has been widely used in lapidary workshops as a relatively cheap abrasive, commonly known in the trade as carborundum. Wheels of bonded materials, such as silicon carbide grit in a ceramic matrix, have been available since the mid twentieth century. Bonded tools are particularly advantageous for working vesicular stones such as the material of this skull, avoiding the need to use loose abrasive slurries. Silicon carbide grits are darkly-coloured and likely to penetrate cavities in the surfaces being worked, causing unacceptable levels of discoloration and increases in opacity to finished pieces.

5. Marketing and acquisition of British Museum skull

Details relating to the early history of the British Museum skull were found in the archives of the British Museum and the Smithsonian Institution. They mainly concern the activities of the French antiquarian collector, dealer and enthusiastic student of ancient Mexico, Eugène Boban Duvergé. Manuscripts in the Bibliotheque National and the Musée de l'Homme in Paris and the Hispanic Society of America, New York, are also informative.

Boban lived in Mexico City from1850 to 1869 and, during the French intervention (1863-1867), had a shop in the centre of town, advertising himself as Emperor Maximilian's antiquarian (Maillefert, 1867). In 1865, Boban became a member of the French scientific commission, and in this capacity formed a collection of some 2000 pre-Columbian artefacts. Their exhibition in Paris in 1867 was probably the most extensive display of Mexican antiquities to have been held in Europe at that time. Two small crystal skulls were listed in the catalogue.

Boban left Mexico in the hope of selling his Mexican collection and establishing himself as an expert in pre-Columbian artifacts, making Paris his base from 1869 to 1885 (and from 1887 until his death, *c.* 1908). He continued to add to his collection, purchasing artifacts from travelers and broadening the collection to include ancient and ethnographic artifacts from other continents. A third, larger crystal skull, currently in the Musée du Quai Branly (mentioned above in the **Introduction**), was added to the collection between 1867 and 1875, when a large part of the pre-Columbian Mexican section was sold to Alphonse Pinart (Rivialle, 2001, p. 354).

Although no crystal skulls were included in a Boban Paris sales catalogue of 1878, one was listed in the subsequent catalogue of 1881. The dimensions correspond to the life-sized carving that was in due course to be purchased by the British Museum. It was described as an excellent example of lapidary art.

In 1885, having acquired a considerable reputation as an expert on antiquities, Boban returned to Mexico City and opened a shop, the *Museo Cientifico*. A collection of human skulls from Mexico and other parts of the world featured among ancient and ethnographic exhibits. The life-size rock crystal carving of a skull, evidently unsold in Paris, was displayed alongside the human examples as a '*pieza unica en el mundo'* without details of provenance or date. Meanwhile, Boban formed a brief partnership with Leopoldo Batres, the inspector of archaeological monuments appointed by President Porfirio Diaz; the two attempted to sell the skull as an ancient Mexican artifact to the Museo Nacional de Mexico. The carving was not considered to be ancient and was assumed to be modern glass from Europe. Batres then denounced Boban, who hastily moved to New York and attempted to sell his collection by various means.

In March 1886, William Henry Holmes of the Smithsonian Institution was warned by Wilson W. Blake, an amateur collector of pre-Columbian objects, of the unsuccessful activities of Boban and Batres in Mexico. Blake added in the letter that Boban had bought the skull in Germany. On December 19th 1886, the New York Times reported the skull had been sold at auction to a Mr Ellis (of Tiffany's). The following month, a signed note from Kunz to Boban acknowledges delivery of '*Wooden case for skull'* to be paid for by *'Tiffany & Co. per George F. Kunz'*, establishes that Kunz was also involved in the purchase (Bibliotheque National BN 2408498, # 513). Two years later, Mr Sisson, a Californian businessman, bought the carving. Within ten years, Sisson was made bankrupt and apparently asked Tiffany to find a new buyer for skull. On 5th November 1897, Kunz wrote to the British Museum, recommending the purchase as noted in the **Introduction**.

The evidence found in the archives for the early ownership of the skull contrasts with the account given by Kunz in *Gems and Precious Stones of North America* (1890) and elsewhere. The skull neither appears to have been owned by an English collector nor brought from Mexico by a Spanish soldier as stated there. Instead, it appears to have been acquired by Boban between 1878 and 1881 in Europe, possibly in France where Boban was then based (Walsh, in press b), or Germany as asserted by Wilson Blake.

6. Geological sources of quartz

6.1. British Museum skull

Observations using digital-microscopy of the solid inclusions near the base of the British Museum skull showed clusters of small (*c*. 20-50 µm), opaque to translucent, green crystals. At high magnification, individual pseudo-hexagonal crystals, sometimes in 'vermiform' stacks with distinctive planar partings were observed (Fig. 5).

Numerous fluid inclusions, in the size range 5-30 µm, occur mainly in curviplanar groupings. They show a preferred lateral orientation across the skull and sometimes display distinctive 'en echelon' features (Figs. 1a and 6a). These characteristics are indicative of a pseudo secondary (PS) or secondary (S) origin, resulting from the healing of strain-induced micro-fractures during or after primary crystal growth according to the criteria of Roedder (1984, p. 644). Rarer, isolated clusters of generally larger, 20-40 microns, inclusions are interpreted as primary (P) in origin. Most inclusions in the quartz have an irregular shape. They contain a colourless liquid and a small rounded vapour bubble, with the proportion of liquid to vapour appearing more or less constant at *c*. 80-85% (Fig. 6b). No daughter minerals were identified, and all inclusions in the sample are classified as simple two-phase aqueous types.

The similar liquid-vapour ratio for the S/PS and P inclusions suggests that they were all trapped from homogeneous aqueous fluids under similar temperature-pressure conditions. Based on the method devised by Shepherd et al. (1985, p. 126) using liquid vapour ratios at room temperature and assuming moderate formation pressures, the trapping temperatures were estimated to have been in the range of 200-450°C. This is indicative of a moderate temperature mesothermal geological environment, rather than a lower temperature epithermal one (*c*. 100-350°C). A higher temperature (> *c*. 400°C) hypothermal environment related to deep seated igneous activity, is not favoured by the absence of daughter minerals.

The characteristic pseudo-hexagonal form of the green solid inclusion clusters combined with semi-quantitative EDX elemental analysis of a sample (showing the major elements, O, Si, Fe, Al, Mg) are consistent with a member of the chlorite group of minerals (Deer et al., 1992, p. 696). Raman spectra obtained from the mineral sample confirmed that the green inclusions are an iron-rich chlorite. Raman analysis on similar inclusions within the quartz skull was not successful as the convex surfaces dispersed rather than focused any useful Raman signals from the solid (and liquid) inclusions.

Chlorites typically form in low to medium grade metamorphic environments at low temperatures up to about 400°C, consistent with the above estimates from fluid inclusions. Iron-rich varieties also form by interaction of hydrothermal fluids with rocks containing high proportions of Fe-Mg minerals such as basalts or their intrusive equivalents (op. cit.). Hyrsl (2006) reviewed the solid inclusions that typify quartz from different geological environments. In his eight-fold classification, chlorite is only listed in the *Alpine fissure* category that corresponds to the mesothermal, greenschist facies metamorphic environment. Notable occurrences cited within this group include Bahia and Minas Gerais in Brazil, Arkansas, USA, Nepal and the Swiss and Austrian Alps, but not Mexico.

The *Photoatlas of Inclusions in Gemstones* (Gubelin and Koivula, 2005) provides further insight into the likely province of the quartz used for the British Museum crystal skull. The publication contains several illustrations of chlorite inclusions from the localities above. Some are from the Minas Gerais region of Brazil but the most striking (p. 205) shows typical vermiform habit in rock crystal from Madagascar, a feature these authors state '*is very often observed in quartz from Anbatomanohina'*. On the basis of the evidence of the inclusions, the most likely source for the large clear single rock crystal used for the British Museum skull is Brazil or Madagascar.

6.2. Smithsonian skull

The white quartz of the Smithsonian skull is too cloudy to enable clear imaging of the fluid inclusions, precluding useful comment on the geological origin of the quartz. This variety of quartz is relatively common with many potential sources, including deposits in Mexico and the USA.

7. Discussion: dating of the skulls

The present investigation of working methods is fully consistent with earlier views that traditional pre-Columbian lapidary technologies did not use the wheel, and used instead a range of hand-held tools that included saws, files and solid rotary drills. Natural tool materials such as stone, wood and bamboo were used. No evidence was found for metal lapidary tools. However, evidence was found to support the view that pre-Columbian abrasives may have included abrasives harder than quartz, such as emery/corundum. In contrast, wheels were used extensively in the manufacture of the British Museum skull. The makers of the skull worked with hard abrasives such as emery or diamond. The Smithsonian skull yielded abundant evidence for rotary tools. Carborundum, a hard modern synthetic abrasive was used, probably in bonded tools.

These results indicate that both skulls were made in post-Columbian times and the Smithsonian skull is a product of the twentieth century, probably shortly before it was bought in Mexico City. While the tool marks do not allow such a precise dating of the British Museum skull, the evidence suggests that Boban acquired it between the sales of 1878 and 1881. The contradictory stories offered for the early ownership of the skull and, in particular, the denouncement of Boban by Leopoldo Batres and Wilson W. Blake, strongly suggest that the skull was manufactured in the latter part of the nineteenth century, probably in Europe where it was acquired by Boban.

It is of particular pertinence to the present study that not only was it possible to distinguish pre-Columbian from early modern working methods but also early modern from more typical twentieth century technologies. This demonstrates the power of the methodology to distinguish lapidary technologies, and reinforces our view that our conclusions are robust.

The modern origins for the skulls are fully supported by the provenance study of the quartz, which suggests that the quartz crystal of the British Museum skull is unlikely to have originated in Mexico and that the European Alps, Brazil and Madagascar are possible sources, each noted for gem quality quartz from appropriate geological environments.

Documentary evidence shows that large blocks of rock crystal were found sporadically in European Alpine sources during the sixteenth and seventeenth centuries (Manfred Wild of the lapidary company Emil Becker, 55743 Kirschweiler, Am Franzenstein 7, Germany, personal communication, 2007). However, these sources were largely exhausted by the nineteenth century and, by the end of the eighteenth century, a considerable amount of rock crystal was obtained from Madagascar by the French for their workshops and distribution in Europe (Bauer, 1968). Intermittent civil wars in Madagascar followed and it was not until 1868, that France was formally granted commercial access to the northwest coast of the island, and a French protectorate was established in 1885.

The sources of rock crystal in Brazil remained largely unexploited until the early decades of the nineteenth century, following the initial settlement of German farmers in that country. The material was first exported to Germany during the 1830s, regular supplies reaching the workshops of Idar Oberstein by 1840. Initially, this was collected as water-worn pebbles from secondary sources along rivers on the eastern seaboard. The discovery of primary sources in the Brazilian Shield led to the export of larger crystals on a regular basis in the latter part of the nineteenth century. By 1896, Bauer noted that supplies of rock crystal from Brazil were dominating European and American markets.

An indication of the availability of large blocks of quartz in the second half of the nineteenth century is reflected by the size of crystal balls worked at Idar Oberstein between about 1870 and 1900 (Manfred Wild, personal communication, 2007). These were carved mainly from Madagascan or Brazilian quartz as spherical 'hand coolers' for the ladies of Venice; they were also sent out to Brazil and Uruguay for the German settlers. Most were 5-7 cm diameter, similar in size to earlier Roman and Renaissance examples. Others were larger, *c*. 10 cm diameter or as much as 15-20 cm diameter. It seems unlikely that crystals suitable for the skull would have been available in Europe from Madagascar or Brazil much before 1870.

8. Conclusion

The evidence from the investigation of lapidary technology, archival research and mineralogy combine in an elegant and powerful way to demonstrate that the skulls under consideration are not pre-Columbian. They must surely both be regarded as of relatively modern manufacture. Each skull was probably worked not more than a decade before it was first offered for sale.

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Figure captions

Fig. 1. (a) Rock crystal skull, 1898-1 British Museum, *c*. 15 cm high, 13.5 cm wide, 21 cm deep; (b) facial features and *temporal fossa* at the side; (c-e) SEM images of moulds of carved features (recessed features on the skull protrude upwards on the moulds). (c) Annotated, oblique view of the end of the mouth and two teeth (see text): the cuts along the additional narrow parts of the teeth (marked on upper tooth) and the mouth (arrowed) are convex here and reflect their concave depth in the skull, consistent with rotary wheel-cutting. The parallel striations retained in the polish along the *temporal fossae* (d) and on the base (e) are also wheel-cut**.** Natural flaws in the quartz surface protrude upwards on the mould (e): drag marks made by the abrasive reflect the use of a high-speed cutting action from left to right of the image. Although not to the same scale, the striations are finer in (d) than (e): finer abrasive was used for finishing the temporal fossae than the base, prior to polishing. (British Museum photographs)

Fig. 2. (a) White quartz skull with hollow cranium, # 409954 Natural History Museum, Smithsonian Institution, *c*. 25.5 cm high, *c*. 22.8 cm deep (Smithsonian photograph)**;** (b-c) SEM images of moulds of carved features (British Museum photographs). (b) The moulded details of the teeth and mouth are similar to those in Fig. 1c, worked with rotary wheels. (c) Groups of fine parallel striations on the internal surface of the cranium lie across the image and are consistent with rotary tools; the coarse striation (arrowed) was probably made by an 'improperly dressed' bonded wheel (see text).

Fig. 3. (a) Rock crystal goblet with cup-shaped hollow base, 10.105605 Museo de las Culturas de Oaxaca, Mixtec culture, *c*. AD 1200-1521, 8.8 cm high. (b) SEM image of the moulded details of the internal surface of the goblet: single striations in random orientations are consistent with non-rotary tools. (British Museum photographs)

Fig. 4. A lapidary teaching his son uses a stone tool to saw individual beads from a preformed perforated column (Codex Mendoza). The painting is reproduced by kind permission of Bodleian Library, Oxford. (Permission will be sought)

Fig. 5. Photomicrograph of a cluster of solid inclusions showing pseudo-hexagonal and stacked vermiform crystal shapes (arrowed), characteristic of a chlorite mineral (Height of field 2.3 mm). (British Museum photograph)

Fig. 6. (a) Curviplanar groups of secondary fluid inclusions, viewed from top of skull. (b) At higher magnification, consistent liquid to vapour ratios are seen in relatively isolated, probably primary, fluid inclusion cluster. (British Museum photographs)

Figures 1a and 1b

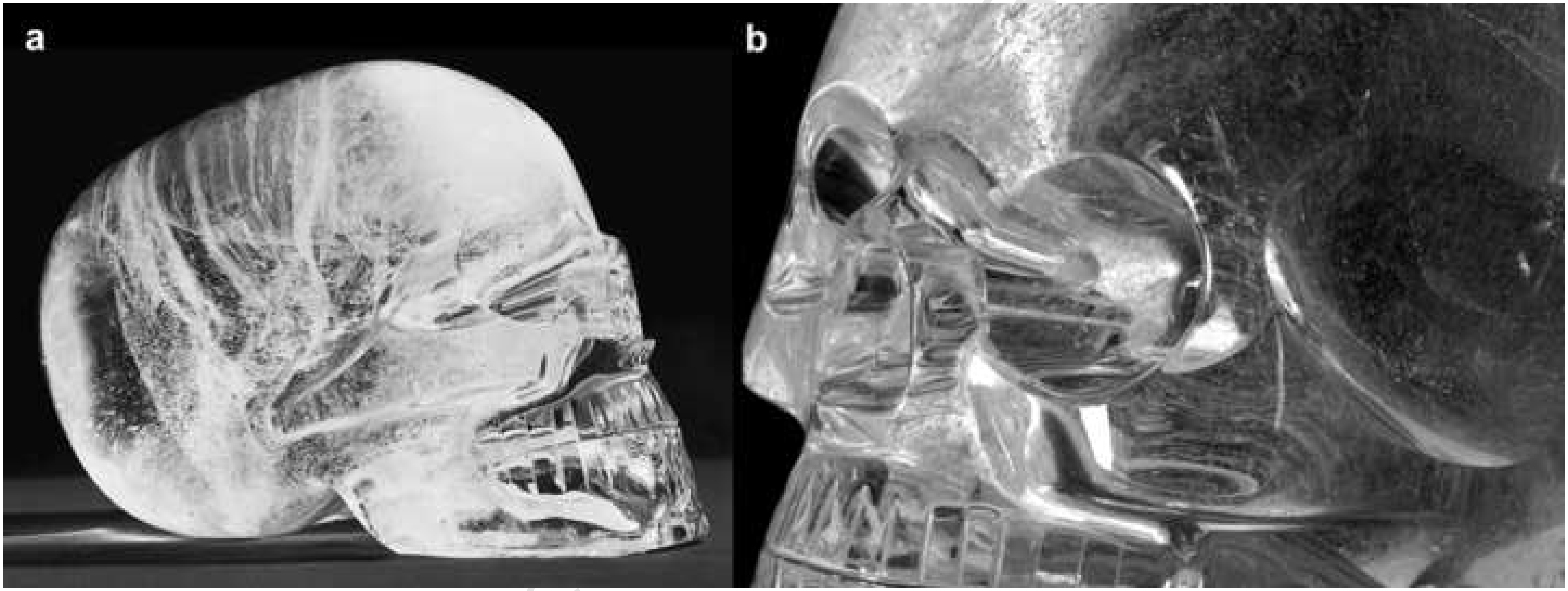
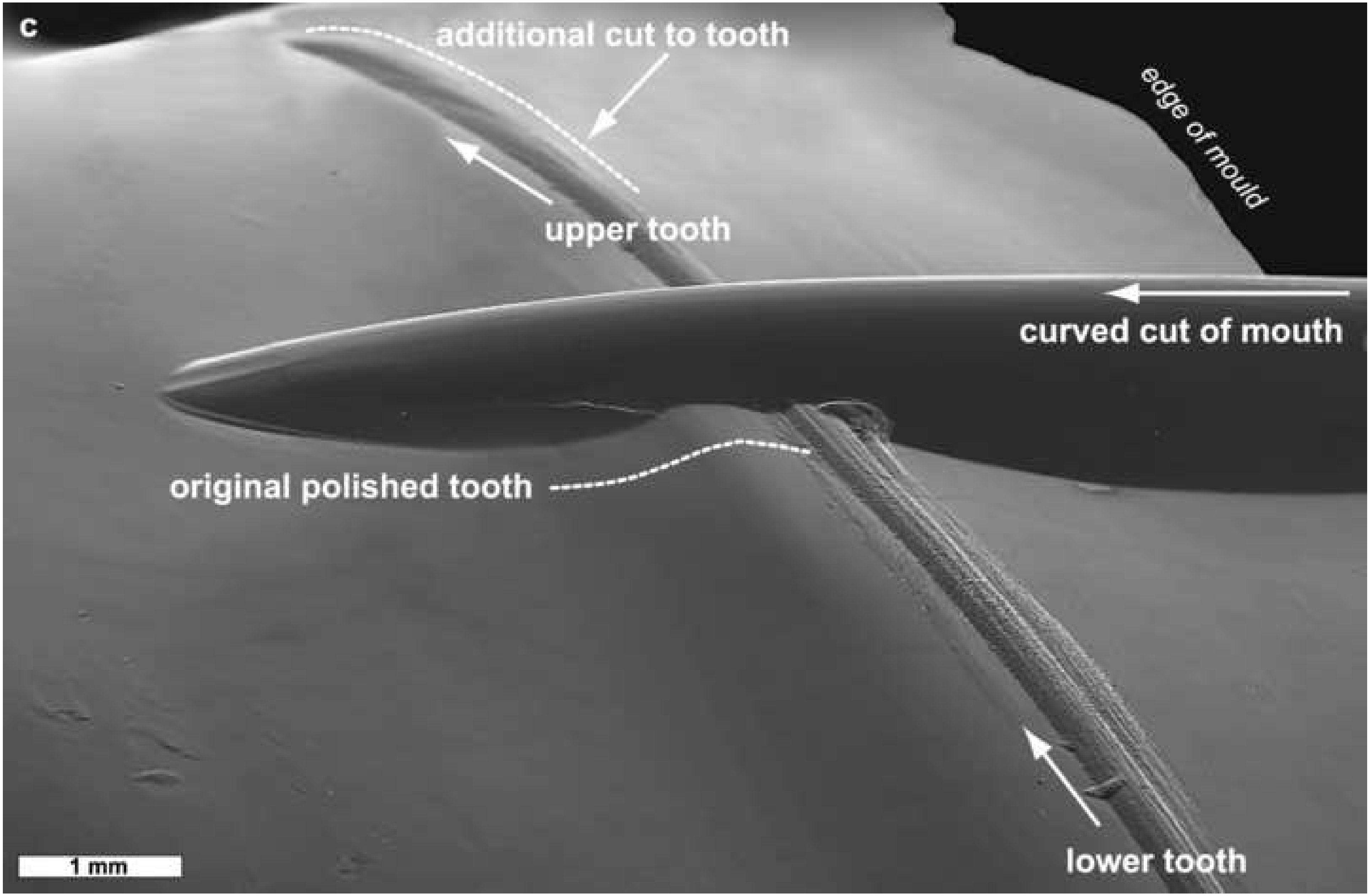


Figure 1c


c
additional cut to tooth
edge of mould
upper tooth
curved cut of mouth
original polished tooth
lower tooth
1 mm

Figures 1d and 1e

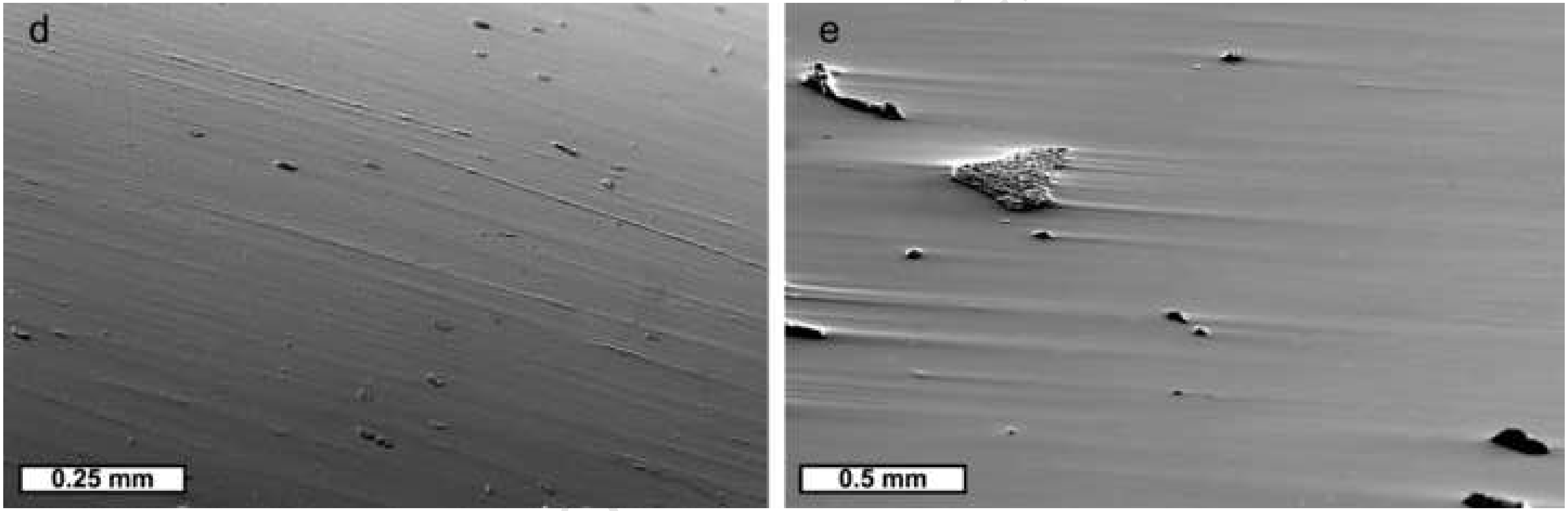


Figure 2a

Figure 2b

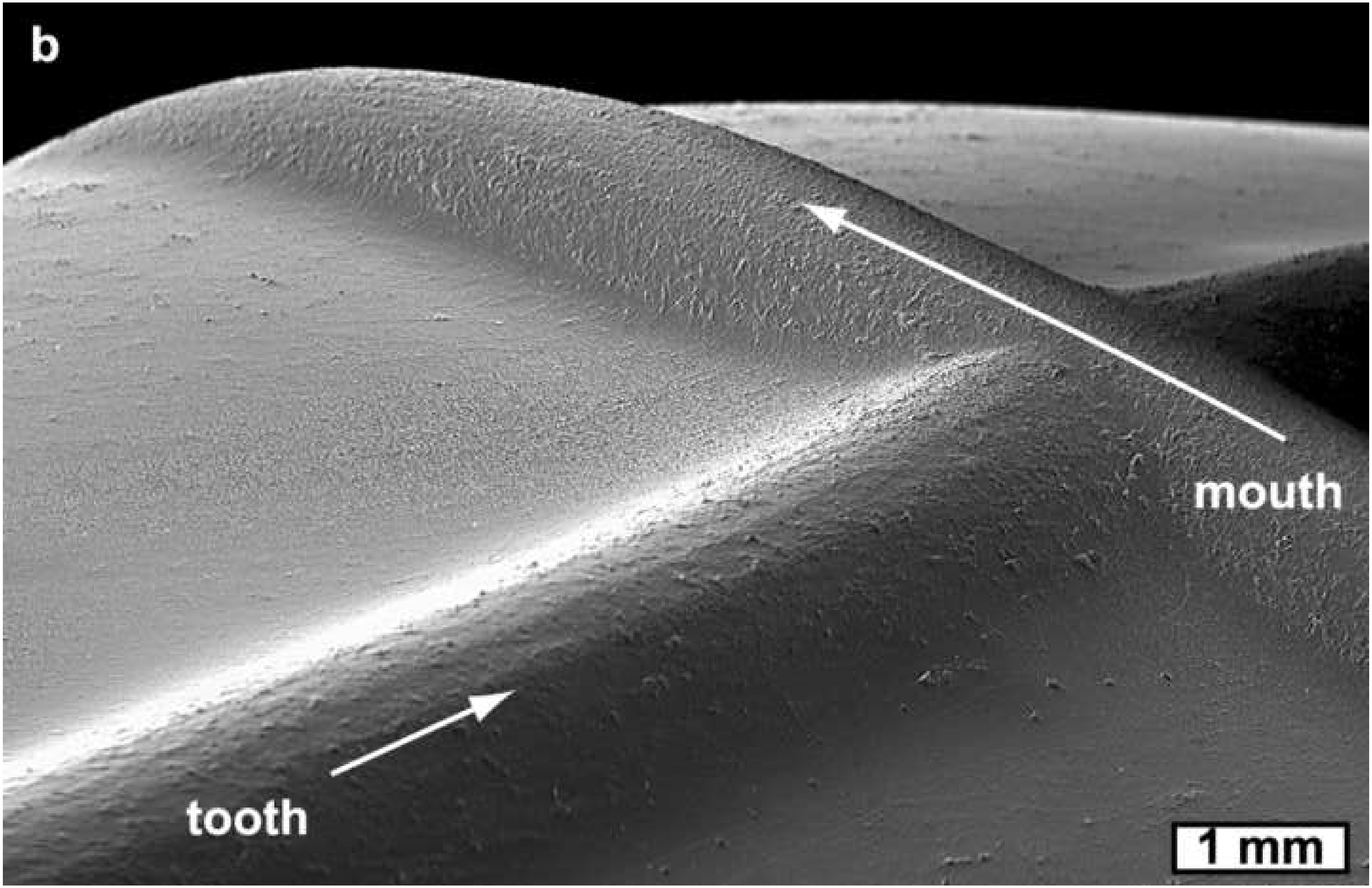


Figure 2c

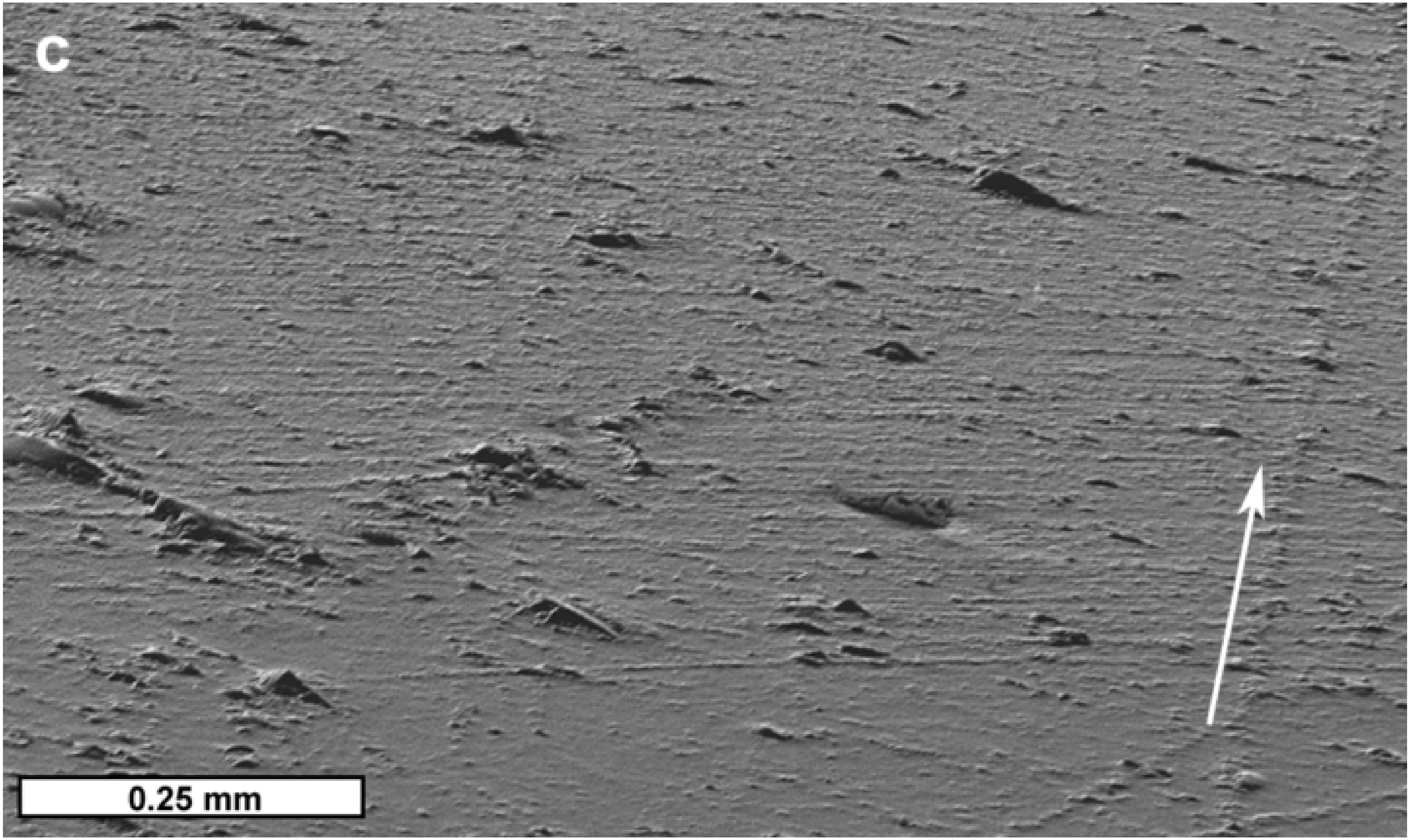


Figure 3a

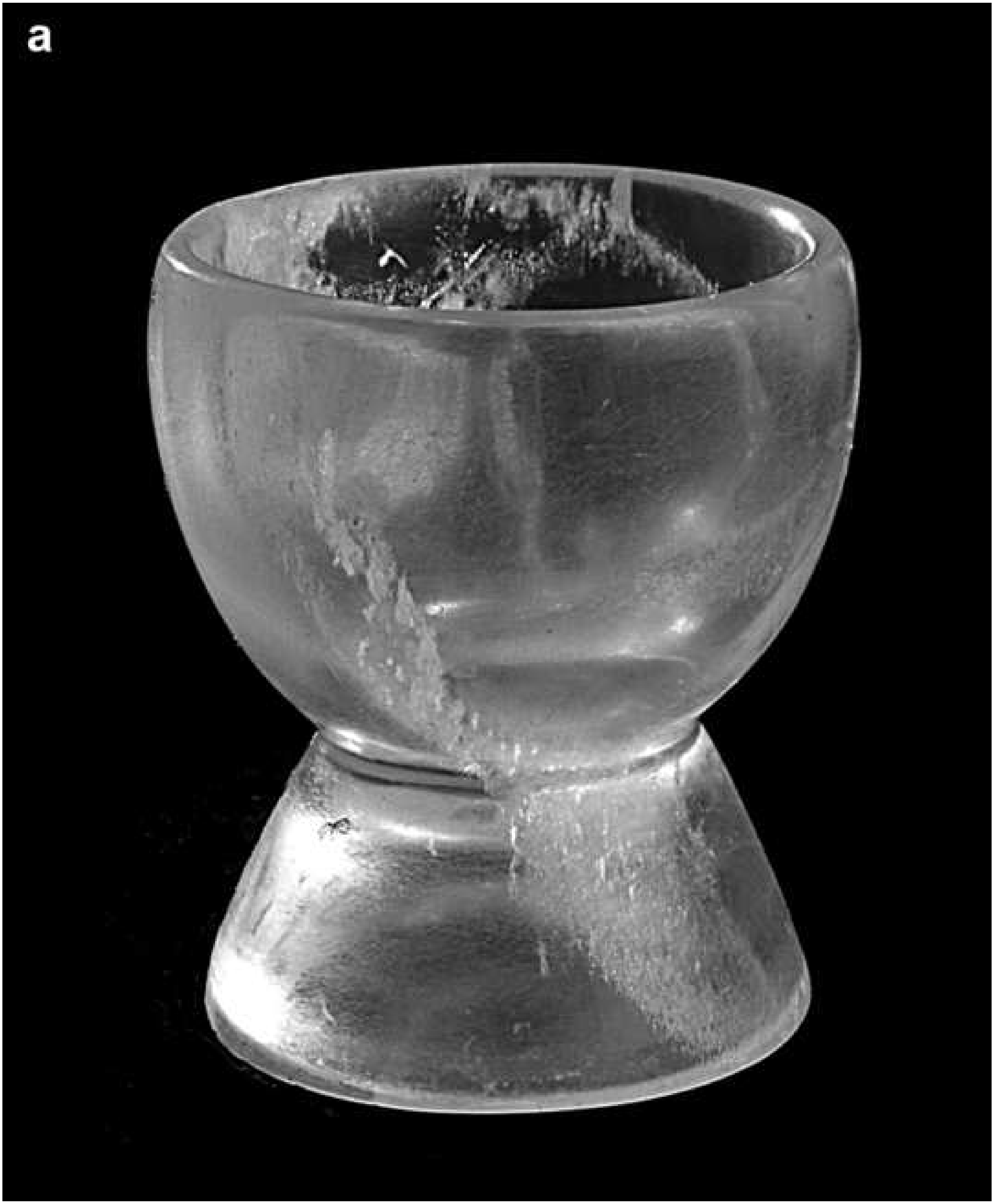


Figure 3b

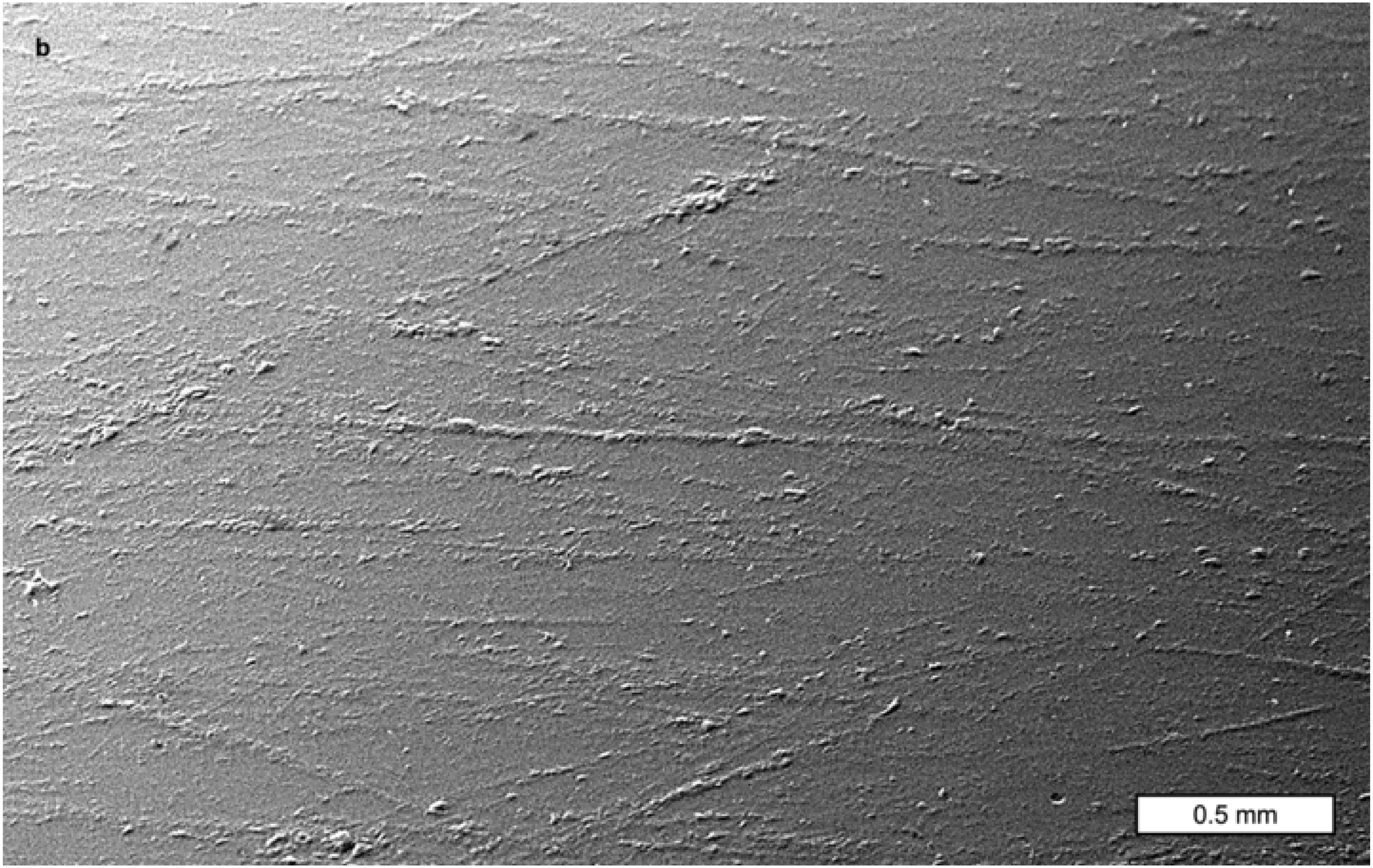


Figure 4

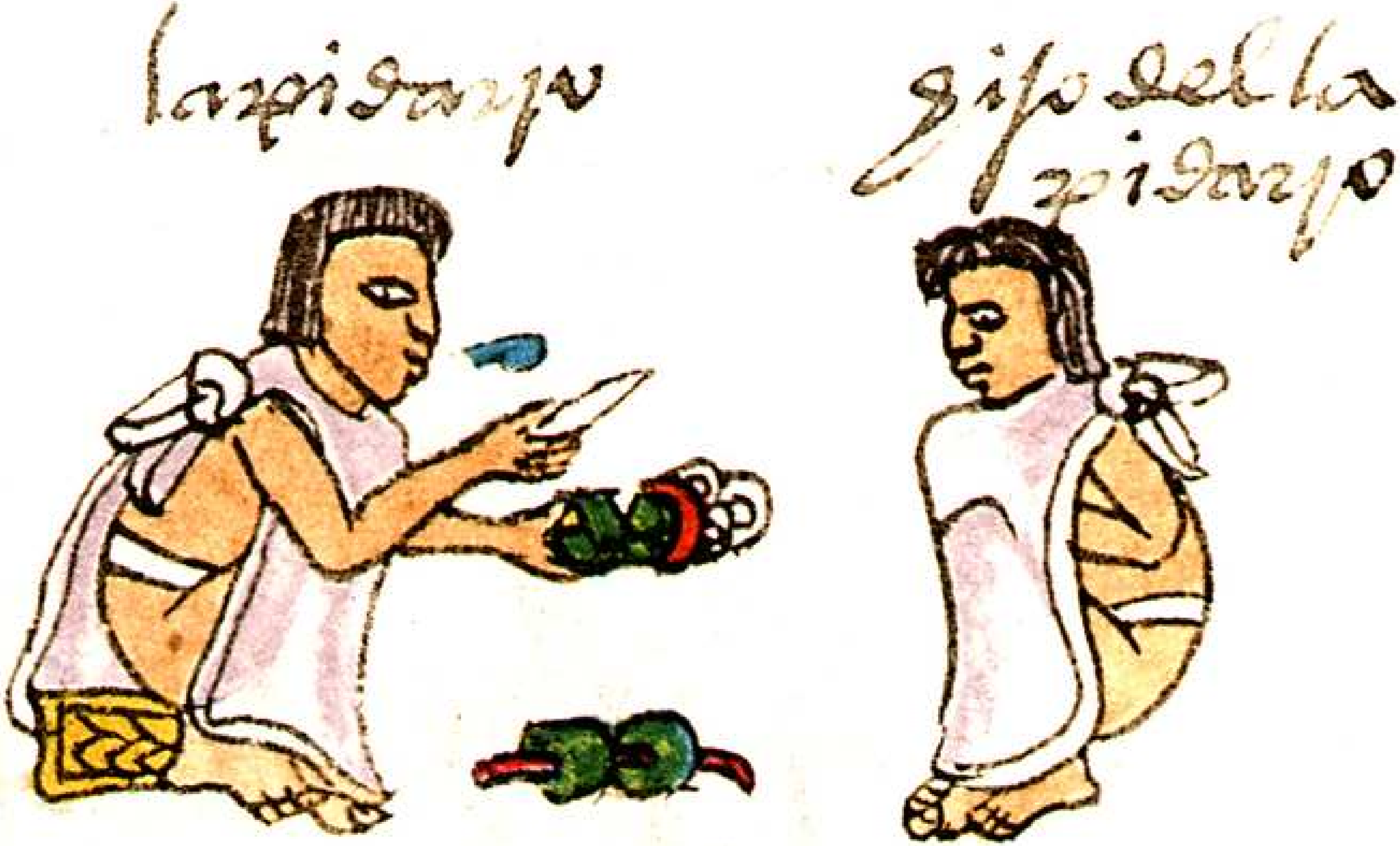


Figure 5

Figures 6a and 6b