Kari A. Kinnunen

MINERALOGICAL METHODS APPLIED TO THE STUDY OF STONE AGE QUARTZ QUARRIES IN FINLAND

Abstract

The mineralogical characteristics of quartz heated in fire-setting (typical ancient mining technique) is analyzed theoretically and from test samples. The diagnostic changes resulting from the heating of quartz are: (1) the bleaching of the original color, (2) the formation of quenching microfractures and (3) the anthropogenic decrepitation of fluid inclusion cavities. It is possible to estimate the heating temperature reached from the quenching microfracture parameters. In the samples from the Kopinkallio quartz quarry in southern Finland (in operation about 9000-8500 BP) the maximum temperature reached in the fire-setting before the water-quenching was estimated to about 480°C. The use of these mineralogical properties is recommended for the verification of suspected Stone Age quartz quarries and other ancient mining sites.

Kari A. Kinnunen, Geological Survey of Finland, Betonimiehenkuja 4, FIN-02150 Espoo, Finland.

INTRODUCTION

In the earliest Mesolithic Stone Age quartz was the principal stone material used for tools in Finland. Elsewhere in Europe it was flint and obsidian, which were mined and used in the same period (see Shepherd 1980). In Finland, the Stone Age quartz quarries are the oldest remains of primitive mining.

One confirmed and several possible Stone Age quartz quarries have been filed in the archives of the National Board of Antiquities of Finland. The Kopinkallio quartz quarry in southern Finland (Fig. 1) is the only confirmed one and for this reason it was selected as an example and a test site. The Kopinkallio quarry and its numerous completed and incomplete quartz implements, manufactured at the site, were originally described by Luho (1956). He (ibid.) dated the quarry to the Mesolithic Stone Age. However, the beginning of the mining operations were in later studies interpreted as somewhat younger, about 9000-8500 BP (discussed in more detail later).

Little is known of the properties of these Stone-Age quartz materials. In most cases they are com-

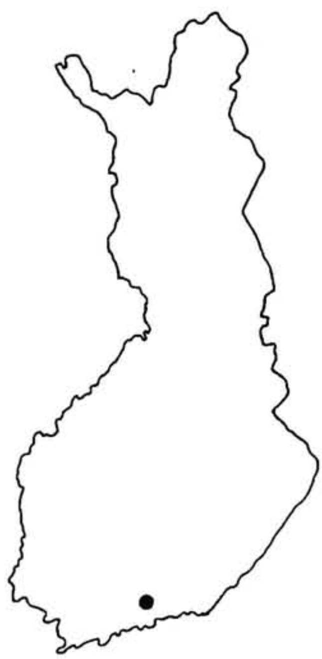

Fig. 1. The location of the Kopinkallio quartz quarry in Southern Finland.

Fig. 2. The largest Mesolithic quartz quarry at Kopinkallio, Askola, in June 1991. The dimensions of the quarry are c. 2.3 x 1.4 x 1.0 m. The concave, spherical walls are typical of fire-setting. Very delicate former loosening of the material can be inferred from the surface textures of the working faces (probably with soft, bone or horn tools). The quartz core of this pegmatite-type deposit has been meticulously removed. All photographs and photomicrographs in this article are taken by the author.

posed of ordinary vein or pegmatite quartz, common in Finnish Precambrian bedrock. Their characteristic feature may be the use of fire-settings in quarrying. The fire-setting was used with water quenching for softening the working face by cracking. The use of this method can be deduced from the large concave surfaces still seen on the working faces of the quarries (Fig. 2).

In this study the mineralogical properties of ancient mine quartz are described. The aim is to define the features which can be used in the verification of the use of fire-setting and thereby in the confirmation of the possible sites of ancient quartz quarries. The results are applicable to more recent mining as well, because fire-setting was utilized parallel with explosives until the late 19th century in southern Finland in small iron and copper mines (see Kinnunen 1989a). The use of heat-treatment possibly as a deliberate method to modify the mechanical properties of the quartz material, and thereby its applicability in Stone Age culture, is proposed in the closing paragraph.

MINERALOGICAL PROPERTIES OF QUARTZ

Many mineralogical properties of quartz may reflect its heating history. Although quartz melts into glass only at a very high temperature (1713°C), which is observed in nature in fulgurites and meteorite impact melts, the comparatively low temperatures reached in camp-fire type heating (up to about 700°C) induce some distinct changes in quartz. The problem is to find these features, which may have indicator value. The properties that can be measured with instrumental methods are first considered.

Both the heated and unheated quartz materials are always composed mineralogically of alpha-quartz when determined (below 574°C) with the X-ray diffraction powder method (Deer et al. 1963). The refractivity indexes of heated quartz show a small increase compared to the unheated quartz (see Frondel 1962). This is explained by the decrease of water content in heating. Heating has been used for the chemical purification of quartz

Fig. 3. A typical quartz fragment from the waste piles of the Kopinkallio quarry, Askola. The dimensions of the fragment are 22 x 16 x 7 mm. Other properties are listed in Table 1 (see Sample 1). The fragment shows quenching microfractures, very light gray color and widespread anthropogenic decrepitation of the inclusions. The estimated quenching temperature of this fragment was 480°C.

raw material (mainly from alkalies and water) in the glass and electronics industry. However, the interpretation of the trace element depletion resulting from heating is very complicated (see Frondel 1962). Under ultraviolet radiation some edges of heated quartz fragments may show weak fluorescence (cf. Gleason 1960).

In some cases the above properties provide useful information, but the interpretation is difficult for archaeological purposes and the chemical analyses are time-consuming and expensive. Therefore, the properties suggested here for the identification of heated quartz are visual characteristics such as color, microfracturing and inclusion decrepitation. They are considered in more detail with the results from the Kopinkallio quartz quarry as an example.

DIAGNOSTIC PROPERTIES OF HEATED QUARTZ

1. Discoloring

In general, bleaching of the original, usually weak smoky, reddish or bluish color of natural quartz is a result of the heating (Fig. 3). According to Nassau (1984), the color of quartz is caused by electron hole centers, which are induced by the heavy metal substitution in the quartz lattice (e.g., Al, Fe and Ti). The colored quartz variants alter to colorless or to milky when heated to 400 – 600°C (Nassau 1984). The heating replaces the electron to its original position and thereby eliminates the color center and bleaches the color. The milky white, iridescent and somewhat pearly appearance

Table 1. Diagnostic properties of three samples selected to represent the main types of quartz, which was heated in the prehistoric fire-setting. The samples are all from the Kopinkallio quarry. The number of polygon diameter measurements range from 22 to 40. The temperature reached in the quenching is estimated using the curve in Figure 4.

Sample	Size, mm	Color Munsell color code	Mean polygon size mm	Estimated quenching temperature, °C	Diameter of the smallest decrepitated fluid inclusions, µm
1	22 x 16 x 7	N8 (very light gray)	1.415	480	3.5
2	28 x 16 x 6	N7 (light gray)	3.195	280	4.6
3	51 x 27 x 22	N7 (light gray)	6.459	230	6.4

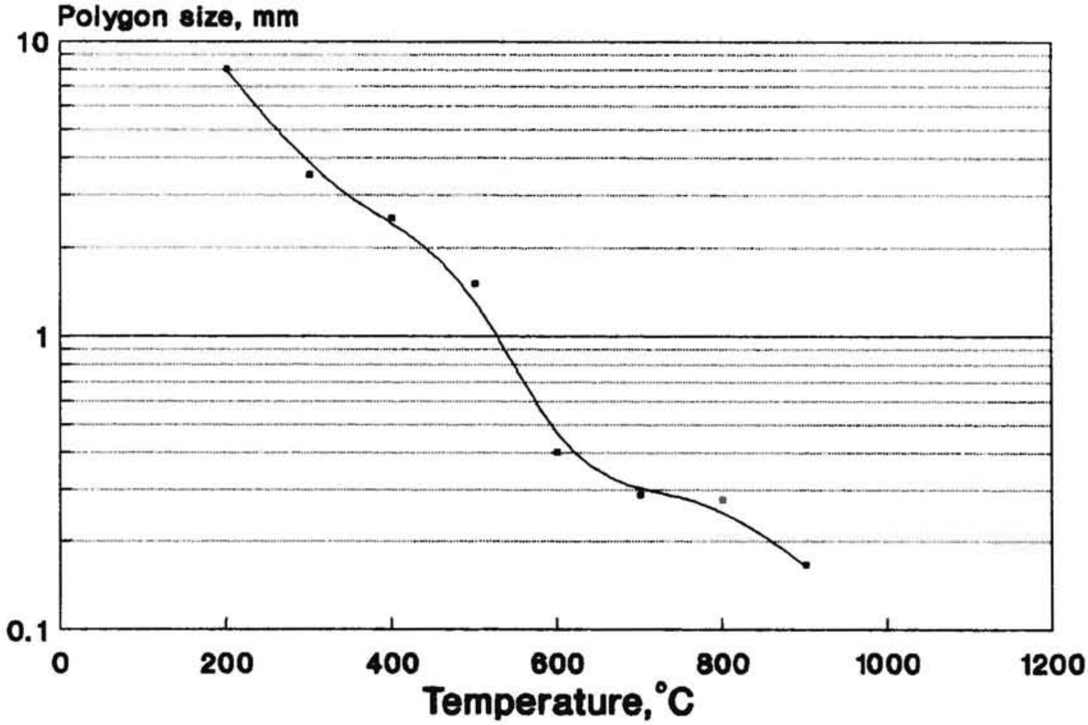

Fig. 4. The experimental data plotted from the experiments performed in China (Yang 1990). The quenching temperature is correlated against the polygon diameters of the microfractures formed in quartz in the quenching experiments.

of the heated quartz (its opalescence) is a result of the specular reflection and the interference of light from the numerous microfractures.

2. *Quenching microfractures*

In addition to discolouring, the heating of quartz typically leads to dense microfracturing. The reason for this is the large difference in the thermal expansion between the two main perpendicular crystallographic directions in quartz. In addition, above 574°C ordinary alpha-quartz is transformed to a more dense mineral modification, beta-quartz (Deer et al. 1963). Quartz converts back to alpha-quartz when the temperature is lowered and microfractures result from this inversion phenomenon. If the heating is stopped with an abrupt lowering of temperature, for example by quenching in water, the resulting microfracturing is especially prominent.

In recent years the microfracturing of quartz resulting from water quenching has been studied experimentally in China for the glass and electronics industry (Yang 1990). Unfortunately most of these studies have been published in Chinese. In this study Yang's results were plotted on a new diagram (Fig. 4), which can be applied to archaeological studies of fire-setting. The fire-setting was practised by pouring or throwing water on the strongly heated working face in order to produce fractures to aid the manual quarrying with primitive chisels and axes. With the diagram it is possible to estimate the maximum temperatures reached in the fire-setting. This is done under the microscope by measuring the mean diameter of the microfracturing polygons in quartz and by comparing the results with the experimental curve in Figure 4.

The quenching microfractures in quartz are typically straight fractures, which are oriented along the rhombohedral and prismatic crystallographic planes of the quartz host. In orientation and shape, they differ from the mechanically induced fractures, which usually are non-orientated and curved, conchoidal fractures. The secondary fluid inclusion planes, in some cases resembling the quenching microfractures, are generally situated in random orientation.

3. Decrepitated inclusion cavities

Occasionally, the heating of quartz leads to the partial destruction of the water-filled microscopic cavities (fluid inclusions) common in all types of quartz in Finland (see Kinnunen 1989b). This is due to the thermal expansion of water, which causes very high internal pressures inside the water-filled cavities leading to their destruction via bursting when the strength of the host quartz is exceeded. The phenomenon has been originally described in Finland and it was termed as *anthropogenic decrepitation* (Kinnunen 1989a).

Natural decrepitation is common, too, but the two types of decrepitation can be identified with detailed microscopy. In anthropogenic decrepitation the fluid inclusions are surrounded by unhealed fractures in the form of a light reflecting and sometimes iridescent water or air film (see Kinnunen 1989a). In natural decrepitation the fractures were formed already in Precambrian times and for this reason they are recrystallized into secondary inclusion planes composed of microscopic fluid-filled vacuoles sealed by secondary quartz (see Fig. 7).

The decrepitation features are diagnostic for fire-setting but the method requires material which originally contained water-rich fluid inclusions (see Kinnunen 1989b). If present, the feature is easy and fast to detect under an optical microscope using so-called thick sections or chip mounts as preparations (see Kinnunen 1986).

RESULTS FROM THE KOPINKALLIO QUARTZ QUARRY

The Kopinkallio quartz quarry is situated in southern Finland (Fig. 1) in Askola, Nalkkila region, to the east of the Porvoonjoki river (Basic map 3022 01, coordinates X = 6715.95 and Y = 422.55, altitude 64.0 m a.s.l.). The largest pit of the quarry area is about 2.3 x 1.4 x 1.0 m in dimension, forming a shallow spheroidal depression on a small rocky hill (Fig. 2). The working faces are concave and dish-shaped, which is typical of quarry walls worked with fire-setting. On the southern side of the pit the presence of small waste rock piles can be inferred.

According to Luho (1956), the quarry and the manufacturing of implements were in operation during the earliest Mesolithic Stone Age. It can be assumed that the quarry is contemporaneous with the Mesolithic sites in the Askola area. According to the shore level displacement studies in Askola by Tynni (1966), the known sites (see Siiriäinen 1974, Matiskainen 1989) are located on the shores of the regressive Ancylus Lake. According to Glückert (1976), the Ancylus regression in the area falls between 8800 and 8300 BP. The detailed Ancylus regression shoreline displacement curve, 14C calibrated and connected to the Mesolithic sites for the Askola region (Fig. 13 in Matiskainen 1989), dates the rapid Ancylus regression to about 9000-8500 BP. This age interval or range is proposed as the most reasonable estimate for the main operation period of the Kopinkallio quartz quarry. However, the artifact typology of quartz may suggest that the Kopinkallio quarry belongs to the end of the Suomusjärvi Culture, extending to about 6200 BP (see Siiriäinen 1981). One possible solution to the problem may be the possible long-continued but periodic use of the quarries from about 9000 to 6200 BP.

Quartz was used in Finland as a local substitute for flint, which was imported principally from the Valdai region now in the present Russia (see Kinnunen, Tynni, Hokkanen and Taavitsainen 1985). According to Luho (1956), small-scale manufacturing of quartz implements was practised at the Kopinkallio quarry, and furthermore, the nearby settlement may owe its existence to the mining operations.

The Kopinkallio quarry supplied raw material (Fig. 3) for manufacturing various stone artifacts. According to Siiriäinen (1981) the typological characteristics suggest following use: (1) scrapers and (2) blades for bone knives. Most of the numerous tool and weapon types suggested by Luho (1956) are according to the more recent typological studies (Siiriäinen 1981) only ordinary flaking products or pieces of cores. The reason for this contradiction in interpretations seems to be the fact that in flaking quartz behaves quite differently to flint and for this reason the flint typology cannot be applied to quartz artifacts (Siiriäinen 1981).

The material quarried at Kopinkallio was composed of pegmatitic quartz segregations and common vein quartz. The quartz is typically milky white or grayish but some pinkish or blueish areas can be observed. The size of the pure quartz aggregates reaches some decimeters. The diameter of the individual subhedral quartz crystals is typically in the range of 1 – 3 mm although some centimeter-sized euhedral crystals have been observed. The quartz crystals are typically lath-shaped, deformed, and strongly recrystallized.

In total 48 quartz fragments originating from the waste piles of the Kopinkallio quarry was studied. Most quartz fragments were characterized by bleaching (Fig. 3), quenching microfractures

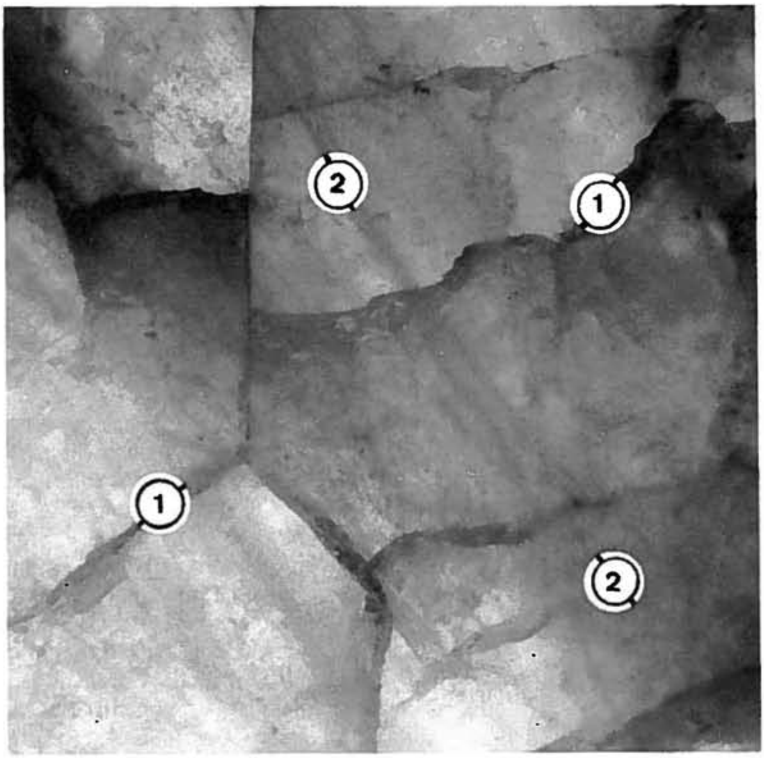

Fig. 5. Photomicrograph of a typical rhombohedral and prismatic microfracture network (1) formed in quenching into quartz. The quartz fragment is from the waste piles of the Kopinkallio quarry (Sample 1 in Table 1). The fractures are partly filled with organic tissue material. Long planes of secondary fluid inclusions (2) cut the quartz crystals. Transmitted light. The picture area is 3.11 x 3.11 mm.

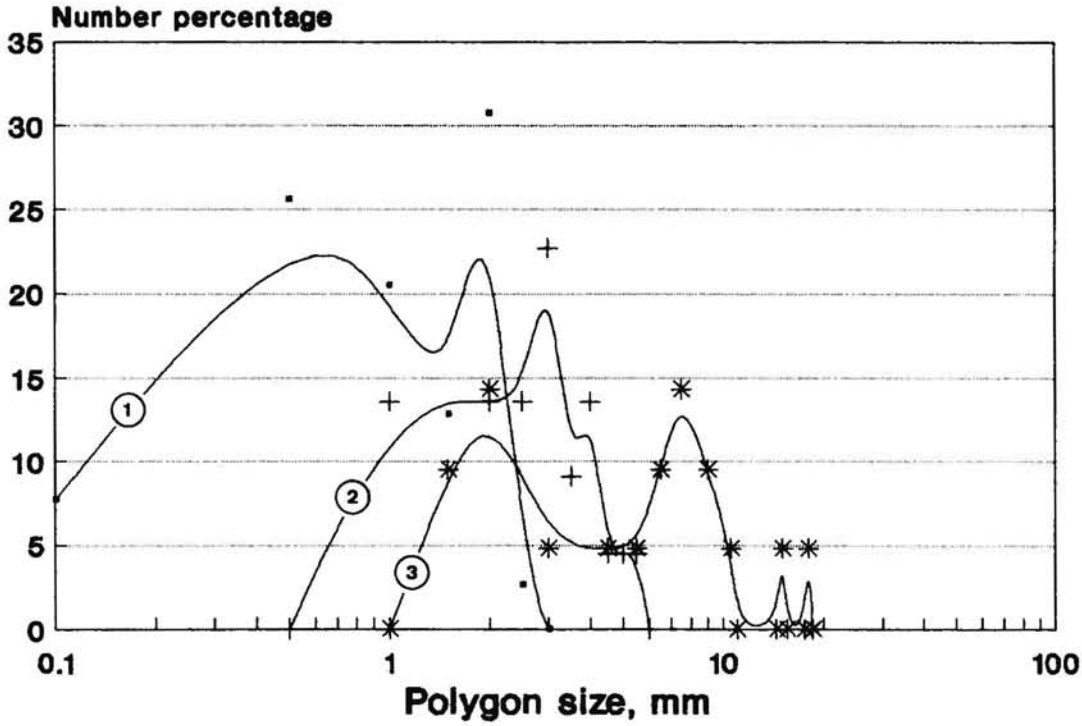

Fig. 6. The frequency distribution of the diameters of the microfracturing polygons measured under the microscope from the quartz samples 1, 2 and 3 from the Kopinkallio quarry (see Table 1 for other data and for the mean polygon sizes).

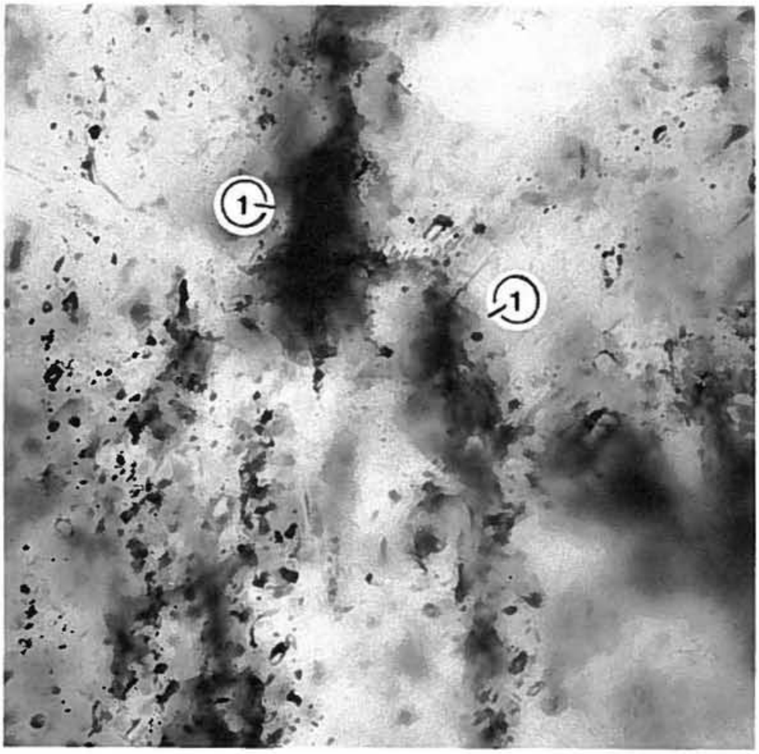

Fig. 7. Photomicrograph of fluid inclusions (1) in quartz decrepitated in fire-setting (anthropogenic decrepitation). The quartz fragment is from the waste piles of the Kopinkallio quarry. Transmitted plane polarized light. The picture area is 0.78 x 0.78 mm.

(Figs. 5 and 6) and decrepitation features (Fig. 7). These properties together with the dish-shaped working faces observed in the quarry prove the use of fire-setting in the mining operation.

The data determined from three quartz fragments selected to represent the quartz material is listed in Table 1. The estimated quenching temparatures range from 230°C to 480°C. The diameter of the smallest decrepitated fluid inclusions and the discoloring are both correlated to the quenching temperature. High quenching temperature is connected with the small diameter of the decrepitated fluid inclusions and the very light gray colour of the quartz material. Many quenching microfractures in the Kopinkallio quartz are filled with fine organic cellular tissues, which have grown from the surface into the fractures (Fig. 8). This explains the typically dark brown color of the fractures and the mottled (dendrite-like) appearance of the ancient quartz fragments (Fig. 3).

APPLICABILITY TO STUDIES ON ANCIENT MINING

The properties shown to indicate ancient heating of quartz are bleaching of the original color, the formation of quenching microfractures and the anthropogenic decrepitation of fluid inclusion cavities. The discoloring and the microfracturing are easy to observe in the field and should find use in inventories of suspected old mining sites as a routine method.

The sources of error in individual observations can in most cases be eliminated by taking in consideration the following points. (1) The color of quartz varies widely and in some deposits (especially in some quartz veins) the color can be white originally. (2) Microfracturing as such without any information on the fracture orientations is not sufficient evidence. Fractures can be induced in quartz likewise by blasting, mechanical shock, freeze-thaw mechanisms etc. (3) The heating may have originated besides fire-setting in forest fires, ordinary camp fires, lightning etc. (4) One mineralogical source of error may in some cases be the natural decrepitation of fluid inclusions (see Kinnunen 1989b). Most of the misidentifications can be avoided with careful archaeological field work connected with detailed microscopy in the laboratory.

Especially forest fires are a serious source of error in many archaeological field studies. Tolonen (1983) has estimated on the basis of paleo-ecologi-

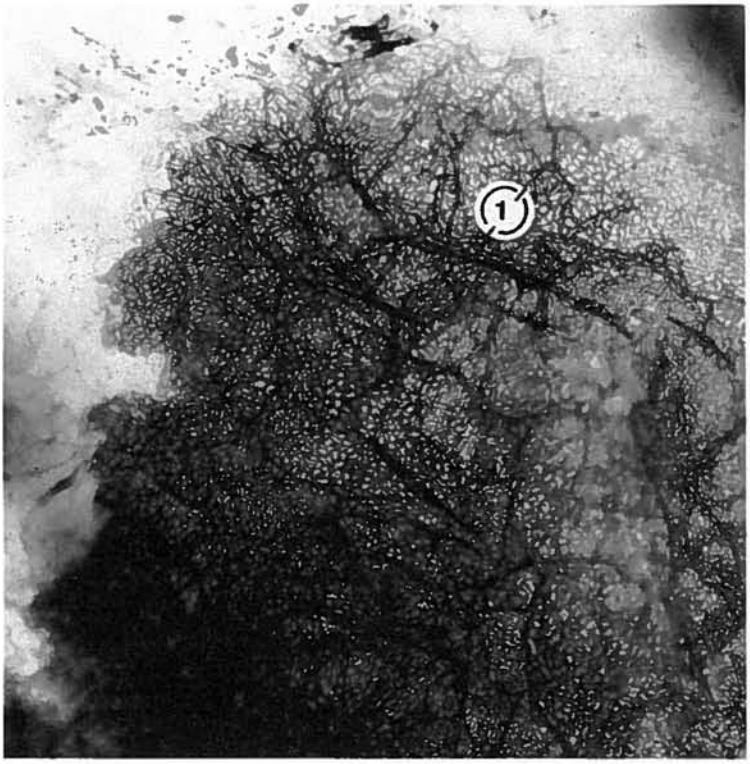

Fig. 8. Photomicrograph of a quenching microfracture in quartz, waste piles of the Kopinkallio quarry. The fracture is partly filled with organic tissue material (1). These fractures give the typically mottled, dark brown appearance to the ancient and long-buried heat-treated quartz (see Fig. 3). Transmitted light. The picture area is 0.78 x 0.78 mm.

cal data that the mean interval of natural forest fires in southern Finland was about 200 years. In theory, the changes in quartz caused by natural forest fire are similar to the changes formed in man-made fire-setting. However, the fire front in forest fires moves rapidly over the target area whereas in fire-setting the long-continued heating (at least hours) is a rule. Additionally, the fire-setting included quenching with water whereas in forest fires the cooling has been slow. Lastly, in the rock cliffs, where the assumed quartz quarries are typically situated, the inflammable surface soil layer is usually very thin and trees and shrubs occur only sporadically. For these reasons, it can be concluded that the forest fires do not form a serious source of error for the mineralogical observations described here, provided that a sufficient number of quartz fragments are studied.

IMPLICATIONS ON MANUFACTURING TECHNIQUES

The mineralogical properties characterizing heat-treated quartz suggest the following questions.

(1) The heating temperatures and the quenching method used were perhaps deliberately adopted for the production of specific sizes and shapes of quartz fragments for manufacturing small artifacts. Yang (1990) has found that the shape and size of the quartz fragments formed depends on the quenching temperature. In this case, the statistical interpretations of length/breadth-ratios, as commonly used, may be misleading in the typological context.

(2) Fire-setting was perhaps practised in order to obtain high-quality raw material from the quarries – not just to simplify the quarrying operations. With simple hammering, quartz is badly microfractured, which complicates later manufacture by flaking and retouch. If so, the quartz tools in museum collections originating from Kopinkallio and other quarries should reveal at least some of the described diagnostic changes formed in heat-treatment.

(3) Heating was perhaps a way to alter the mechanical properties of ordinary quartz more to resemble those of flint. Siiriäinen (1981) has emphasized that the control of ordinary quartz material in flaking was much weaker than with flint. Only very high-quality quartz (rock crystal, smoky quartz, rose quartz) have been manufactured into finely made retouched artifacts (as noted by Ma-

tiskainen 1989, p. 81). Some of these were perhaps made for ornamental use.

In heat-treatment, quartz is polygonized and its flaking properties are thereby altered. Retouching is more difficult than with unheated quartz. Interestingly, the absence of retouching in the Kopinkallio artifacts was noted by Siiriäinen (1981) from the material originally described by Luho (1956).

One explanation to this problem was noted in the experiments performed by the author using heated and unheated Kopinkallio quartz fragments against wood. It was observed that heat-treated quartz is an excellent tool (scraper) against wood compared to the unheated quartz, which blunts rapidly. The heat-treated quartz behaves much like a grinding stone supplying automatically new sharp cutting edges in continued work (because of the constant loosening of the polygonized grains). This may explain the scarcity or absence of wear-marks and of sharpening retouch and the primitive typology of the Kopinkallio quartz artifacts. If so, the heat-treated quartz may have been the ideal material for almost complete, disposable type implements, preferably scrapers, the raw material for which could be obtained easily and in abundance from local bedrock sources.

ACKNOWLEDGEMENTS

In the summer of 1991, Dr. Risto Tynni guided me with his detailed knowledge on the geology and archaeology of the Askola region during my visit to the Kopinkallio quartz quarry. Professor Ari Siiriäinen (Helsinki University, Department of Archaeology) kindly read the manuscript and suggested many valuable corrections and additions. I address my genuine gratitude to these pioneers.

REFERENCES

Deer, W.A., Howie, R.A. and Zussmann, J. 1963. *Rock-Forming Minerals.* Vol. 4., *Framework Silicates.* Longmans, London, 435 p.

Frondel, C. 1962. *Silica Minerals. The System of Mineralogy,* Vol. III. Wiley, New York, 334 p.

Gleason, S. 1960. *Ultraviolet Guide to Minerals.* Van Nostrand, Princeton, 244 p.

Glückert, G. 1976. Post-glacial shore-level displacement of the Baltic in SW Finland. *Annales Academicae Scientiarum Fennicae A,* III, 118, 92 p.

Kinnunen, K.A. 1986. Yksinkertainen menetelmä fluidisulkeumien etsintään. Summary: A simple method for pilot fluid inclusion studies. *Geologi* 38, 133-134.

Kinnunen, K.A. 1989a. Anthropogenic decrepitation of fluid inclusions in old mines of southern Finland: signs of fire-setting. *Geological Survey of Finland, Special Paper* 10, 143-145.

Kinnunen, K.A. 1989b. Determination of total contents of fluid inclusions in quartz using modal analysis: Examples from Proterozoic rocks and ore deposits. *Bulletin of the Geological Society of Finland* 61, Part 2, 197-208.

Kinnunen, K.A., Tynni, R., Hokkanen, K. and Taavitsainen, J.-P. 1985. Flint raw materials of prehistoric Finland: Rock types, surface textures and microfossils. *Geological Survey of Finland, Bulletin* 334. 59 p. and 40 photoplates.

Luho, V. 1956. Die früh-mesolithische Steinzeit in Finnland. *Suomen Muinaismuistoyhdistyksen Aikakauskirja* 57, 1-167.

Matiskainen, H. 1989. Studies on the chronology, material culture and subsistence economy of the Finnish Mesolithic, 10 000-6000 b.p. *Iskos* (Suomen Muinaismuistoyhdistys) 8, 184 p. (unpaginated).

Nassau, K. 1984. *Gemstone Enhancement.* Butterworths, London, 221 p.

Shepherd, R. 1980. *Prehistoric Mining and Allied Industries.* Academic Press, London, 272 p.

Siiriäinen, A. 1974. Studies relating to shore displacement and Stone Age chronology in Finland. *Finskt Museum* 1973 (vol. 80), 5-22.

Siiriäinen, A. 1981. Problems of the East Fennoscandian Mesolithic. *Finskt Museum* 1977 (vol. 84), 5-31.

Tolonen, K. 1983. The post-glacial fire record. In: *The Role of Fire in Northern Circumpolar Ecosystems.* Eds. Wein, R.W. and MacLean, D.A. Wiley, 21-44.

Tynni, R. 1966. Über spät- und postglaziale Uferverschiebung in der Gegend von Askola, Südfinnland. *Bulletin de la Commission geologique de Finlande* 223, 97 p.

Yang, J. 1990. Studies on quenching cracks of quartz crystals. *IMA 15th General Meeting,* 1990 Beijing, Abstracts, 218-219.