V. PETROGRAPHIC CHARACTER OF CLASSIC MARBLES

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Petrography.

Rocks are aggregates of mineral grains. Ideally each grain is a crystal or crystal fragment with a specific chemical composition - quartz SiO_2, calcite $CaCO_3$, potash feldspar $KAlSi_3O_8$ and so on. Standard petrographic procedure consists in microscopic examination of thin sections of rocks - about 1 cm in diameter, 0.02-0.03 mm thick, mounted on glass. Examination is carried out in polarized light, for this permits determination of optical properties related to crystal symmetry and peculiar to each mineral species. By this means two sets of petrographic characteristics of any rocks emerge; and both give valuable information as to the origin and history of the rock:

(1) The mineralogical identity of the component grains, the principal mineral constituents of most rocks being only half-a-dozen in number.

(2) Their mutual geometric relations which define the rock texture. The respective textural characteristics of volcanic rocks that have crystallized from melts, of sandstones laid down in water, and of metamorphic rocks that have recrystallized in the solid at high temperature and pressure, can be distinguished as such almost at a glance.

Nature of Marble.

Marbles are mineralogically simple rocks formed by metamorphic recrystallization of limestones (calcareous sediments, mostly originating as beds of shell and other organic debris laid down in clear marine waters). The main constituent is calcite, the common crystalline form of $CaCO_3$; and since statuary marbles are usually selected for purity and homogeneity the great majority contain more than 90 per cent, and some over 99 per cent of this single mineral. A principal component of a few marbles, among them some from the ancient quarries of Naxos, is dolomite, $CaMg(CO_3)_2$. During metamorphic recrystallization calcite crystals have grown to diameters of the order of 0.5 to 2 mm, and now build a closely interlocking mosaic. Metamorphic temperatures mostly lie within the range $250^\circ C$-$650^\circ C$. Under these conditions, maintained in rocks deeply buried for periods of 10,000 to 10,000,000 years, mineral impurities, notably clays and silica, when present, react with the carbonate matrix to produce new and characteristic metamorphic minerals readily identified with the polarizing microscope.

Non-Diagnostic characteristics.

From what I have said it is clear that all statuary marbles have much in common. Nothing of the unique character of marble from an individual outcrop or quarry is likely to emerge from routine chemical analysis, study by X-ray diffraction, or even from superficial microscopic examination by an "expert" lacking wide petrographic experience. Such techniques, valuable though they may be in identifying other materials, will merely tell us that we are dealing with rocks composed principally of calcium carbonate (calcite) with a minor-element pattern (trace of lead, copper, strontium, barium and so on) that is monotonously the same for most marbles. And this leads to a point of significance in evaluating "expert" opinion based on examination of archaeological materials by modern sophisticated techniques. However refined or complicated these may be, their use is justified only where they can yield new or more precise diagnostic information not obtainable by simpler and more commonplace means. A dozen years ago the Fogg Museum acquired a marble statue of Trajan. Critical as to its authenticity and history was the source of the marble from which it was carved. It was submitted to an "expert" who carried out detailed investigation by x-ray diffraction and spectrographic analysis and superficial petrographic examination. From all this there emerged, as could have been predicted by any mineralogist, the information that the Trajan statue is composed of uniform-grained marble with the chemical composition (including trace-element pattern) of almost any marble. Yet, on the basis of this evidence, the material was identified as "second grade Carrara marble;" and this pronouncement became an essential component of a lengthy reconstructed history of the statue, beginning in ancient Rome. It may well be that the story so put together is essentially true. The marble itself may well have come, as claimed, from Roman quarries at Carrara. But no compelling evidence to this effect has been presented; and the marble may equally well have come from any of a hundred sources, known or unknown, within or outside Europe.

Diagnostic Characteristics of Marble in Problems of Archaeology.

How then may petrography be of use in archaeological problems concerning classic marble? We commonly encounter two kinds of problems relating respectively to (1) the possible geographic source of a particular piece of stone, and (2) the possible matching of fragments supposedly broken from the same piece - especially in reconstruction of fragmented inscribed slabs.

Diagnostic petrographic characteristics that may contribute toward solution of such problems are those that reflect the imprint of the particular local episode of metamorphism by which a particular limestone was transformed into a particular marble. Metamorphism, it will be recalled, is a response to long-sustained high temperature and pressure over some period of geologic time. For Greek marbles this was probably during the Paleozoic era - perhaps 400-300 million years ago. The marbles of northern Italy - at Carrara, west of Florence, and at Lasa in the upper Adige Valley - were metamorphosed much later during the growth of the Alps, beginning perhaps 50 million years ago. The temperature-pressure conditions at any broad locality, e.g., in the

Pentelicon-Hymettus area west of Athens, or in the Carrara quarries of Italy, cover a limited range. Moreover, during metamorphism, which also involves intense deformation and flow of marble in the solid state - just as in the forging of red-hot metal - the pattern and degree of deformation are likely to differ from one locality to another; but at any one locality they are likely to be rather uniform.

The useful characteristics that we seek in marble for present purposes fall into three categories relating to texture, fabric and mineralogy:

Texture. The most obvious textural characteristic of a thin section of marble is grain-size. This tends to be highly variable from point to point on a quarry face, or even within a small slab or sometimes in a single thin section. The diagnostic value of the size criterion is correspondingly slight. Three characteristics that reflect deformational history, and so are more uniform in a given outcrop are degree of twinning, grain shape and configuration of grain boundaries.

Twinning. Any crystal subjected to stress at high temperature and confining pressure may respond by internal flow in a pattern dictated by the regular geometric arrangement of its component atoms. Seen in the simplest way the response can be envisaged as mutual displacement of adjacent planar arrays of atoms by analogy with sliding of cards in a card deck. By this means the grain elongates in one direction and becomes flattened in the direction perpendicular thereto. In special cases this process of slip or glide leads to development of thin laminae within which the atoms have become rearranged in a configuration symmetrically related to that in the host crystal. Such a reconstituted layer is termed a twin. Seen beneath the polarizing microscope twins are visible because their optical behavior differs from that of the host (Plate 1). Calcite is a mineral that twins readily under stress - especially at temperatures of less than about 500°C. The degree of twinning shown by calcite in marble tends locally to be rather consistent; it may differ significantly from one locality to another, or even from point to point in one quarry. Contrast the heavily twinned conditions of some grains in a marble from the Greek island of Kos (Plate 2a) with the paucity of twinning in a specimen from Paros (Plate 2c). On the whole twinning is not profusely developed in true classic Pentelic marbles -those from ancient quarry sites on the lower levels of Mt. Pentelicon (Hertz and Pritchett, 1953, p. 75, 77) - or in Hymettan marble from the Hymettan quarries (Plate 3a). It is even less conspicuous in most pure white Carrara marbles (Plate 4).

Shape and outline of grains. In marbles that were strained at rather high temperature without subsequent recrystallization, individual grains show a tendency for local parallel elongation (Plate 1a). Where recrystallization has outlasted deformation - or commoner situation - the grains show no such elongate shape and are said to be equant (Plate 2). Grain outlines may be highly irregular and interlocking (Plates 2, 3). More rarely when high-temperature recrystallization followed relatively cold deformation and was long sustained under stress-free conditions, the resulting grain boundaries tend to be planar. In the ideal case where surface tension at boundaries has been minimized the section shows points at which three boundaries intersect at about 60° (Plate 4a, b). Textures of this kind are characteristic of annealed metals. Combined properties of grain shape and outline are likely to be consistent within the limits of a single slab, or even within a quarry. Much of the high-quality marble from the Carrara quarries has equant grains with planar outlines - what we might call an annealing texture. Most specimens of Greek marble that I have examined - Pentelic, Hymettan or from Paros - have equant grains, often variable in size, with sutured or irregular boundaries. The few specimens that I have seen from Naxos are generally coarse, locally variable in size, equant and with some planar boundaries. Some Naxos marbles consist largely of coarse dolomite with sutured margins.

Fabric. A much more subtle set of structural characteristics, difficult to measure but consistent within a slab or even a large quarry, are what students of deformed rocks collectively term fabric. During rock flow under stress the individual microscopic crystals tend to become aligned in some symmetrical pattern related to that of flow itself. By analogy we may recall the respective patterns of logs in a flowing stream or of clouds in the steady trade-wind sky. It is not only by external shape that elongate grains become aligned. Even in marble whose grains are equant there is a pervasive though invisible pattern of orientation of the principal symmetry axis of the individual calcite grain. To bring out the pattern we must use specialized and rather laborious techniques of microscopy or X-ray analysis (cf. Weiss, 1954; Herz, 1955). But this is by far the most effective tool in problems relating to matching of fragments of statuary or of inscribed surfaces. If fragments match not only in direction and sense of inscription but also in the pattern and orientation of crystal fabric, the chances that they belong to the same slab are very strong indeed. Conversely, failure to match can be demonstrated with certainty.

Mineralogy. Much of the marble from the classic Dionysus quarry on Mt. Pentelicon is streaked sparsely with greyish green aggregates of the common metamorphic minerals chlorite, albite and epidote (Plate 3b) - all recognizable at a glance in a thin section. Occurrence of the same suite of minerals in marble of a temple such as that of Sunion is consistent with a Pentelic source, but is by no means conclusive proof of this; for impurities of the same kind are known in other mables. Some sources can, however, be excluded with certainty. Such is the group of quarries near Apollonia on the northeast coast of Naxos. All Naxos marbles that I have seen are almost pure calcite or dolomite. But if silicate impurities occur within them, it is impossible that they should include chlorite-albite-epidote. General experience of metamorphic petrography shows that this mineral assemblage can form at temperatures no higher than 350°. On the other hand sufficient is known of the geology of Naxos to indicate that in the general vicinity of Apollonia metamorphism was effected at temperatures of the order of 500°-600°C (Schuiling and Oosterom, 1967). Chlorite, albite and epidote could not coexist in this environment.

I have seen very little of Egyptian statuary marbles. Several specimens that I have examined microscopically contain silicates such as forsterite, Mg_2SiO_4, indicating conditions of metamorphism (local high temperature and low pressure) completely inconsistent with classic Greek and many north Italian sources (among these Carrara). The sources are probably local. The Egyptian marbles could not have come from classic Greek quarries. But as far as mineralogical evidence alone is concerned, the source could be located (though I think the probability infinitely small) in the Mojave Desert or the Sierra Nevada of California!

Mineralogical evidence accruing from petrography, relating to our present problem, leads mainly to exclusion of particular alternative solutions. Rarely we encounter evidence of a more positive kind. Some marbles are streaked with red, due to iron-oxide impurity in the form of hematite. Among the specimens collected by Herz from a classic Pentelic quarry is a red variety that in my experience is mineralogically unique. It contains the easily recognized red-to-orange highly refractive calcium-manganese silicate piedmontite. I know of no other marble from Greece or elsewhere that contains this mineral. Yet, by way of due caution, it seems most likely that somewhere, and quite possibly in Greece, another such rock may exist. Any slab of piedmontite-bearing marble found in Greece has most likely, but not certainly, come from Herz' source on Mt. Pentelicon.

Conclusion

Petrographic investigation can contribute a good deal toward solution of problems relating to sources or to matching of marble objects of archaeological interest. Only a start has been made in exploring the petrographic nature and variety of marble at a few classic quarry sites. Much more must be done, preferably by geologists. Badly needed, too, is extensive expert petrographic work on the objects themselves. This must be done by archaeologists, for only they can set up the problems and sustain interest in their solution. Any young student of classic archaeology who might care to include in his university training a few adequate courses in crystallography, mineralogy and petrography could make an immense contribution in this field. This is not so difficult a task as, for example, to master a language such as Russian or even German.

Finally it must be realized that archaeological problems in which the source of marble objects is crucially significant are seldom open to unique solution, Petrographic evidence may rule out certain hypothetical solutions as impossible. Others may be found consistent with the petrographic data, but no more than that. Very rarely a particular alternative may find petrographic support demonstrating probability almost - but never quite - to the point of certainty. But certainty, however much it tinges much of the opinion found in the older literature of classic archaeology and in the reports of some museum "experts," is not the goal of the scientist's quest. The petrographer, viewing from the outside problems of the kind we have been discussing, as clearly set out in the critical essay of Herz and Pritchett (1953) on "Marble in Attic Epigraphy," finds a paradoxical situation: pervading much of the pertinent literature of classic archaeology, as well as the reports of some "experts," there seems to be some reluctance to apply the principles of logic formulated - while some of the ancient quarries were operating, and others as yet unopened - by Socrates and Aristotle.

Acknowledgment

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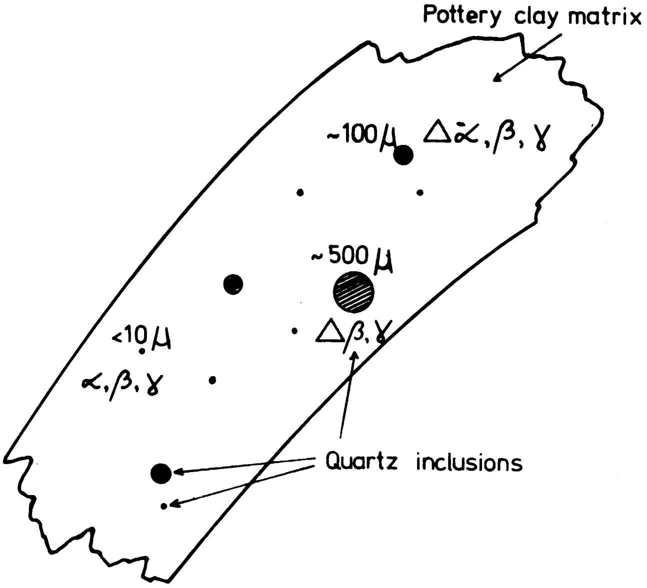

Fig. 3a. Radiation environment of crystalline grains embedded in the pottery clay matrix. For grains of ∼ 100 microns diameter the alpha radiation from the clay is attenuated by approximately 80%. For grains of ∼ microns the alpha radiation is almost entirely attenuated but now even the beta radiation from the clay is attenuated (by approximately 50%).

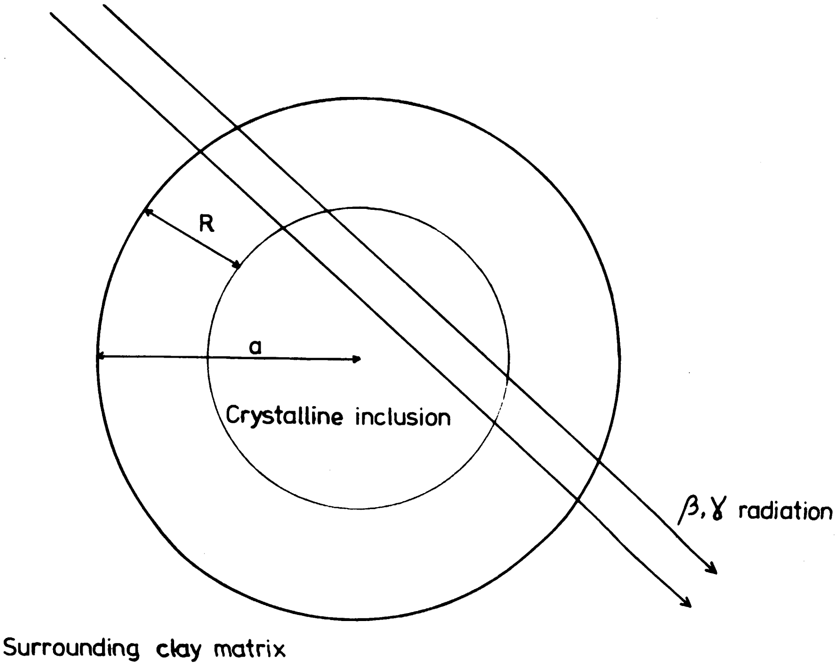

Fig. 3b. Alpha radiation attenuation by large crystalline grains. R is the maximum range of alpha particles in the crystal and a is the radius of the grain. As no alpha particles penetrate beyond a depth, R, into the grain, the inner regions experience only beta and gamma radiation during the burial of the pottery.

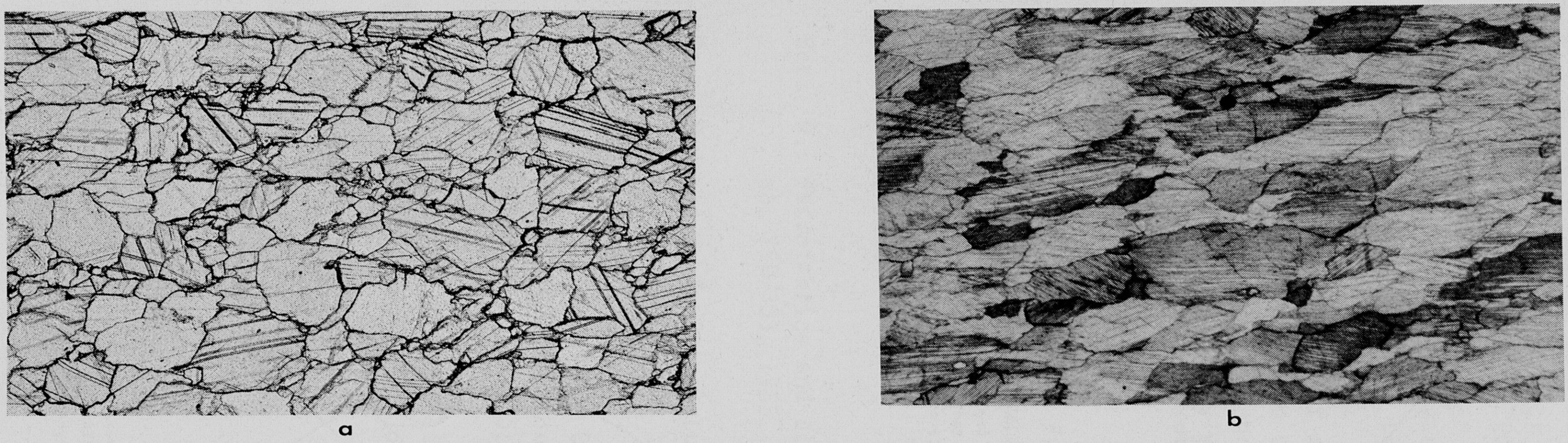

Plate 1. Thin sections of marble, Yule Creek, Colo. Transmitted polarized light. Lamellar structures are twins on $[02\bar{2}1]$ plane.

(a) Undeformed. X 10

(b) Experimentally deformed (shortened 19% by compression at 300°C, 5 kb confining pressure (D. T. Griggs). Note increased incidence of twinning, and grain elongation perpendicular to principal axis of compression. X 15

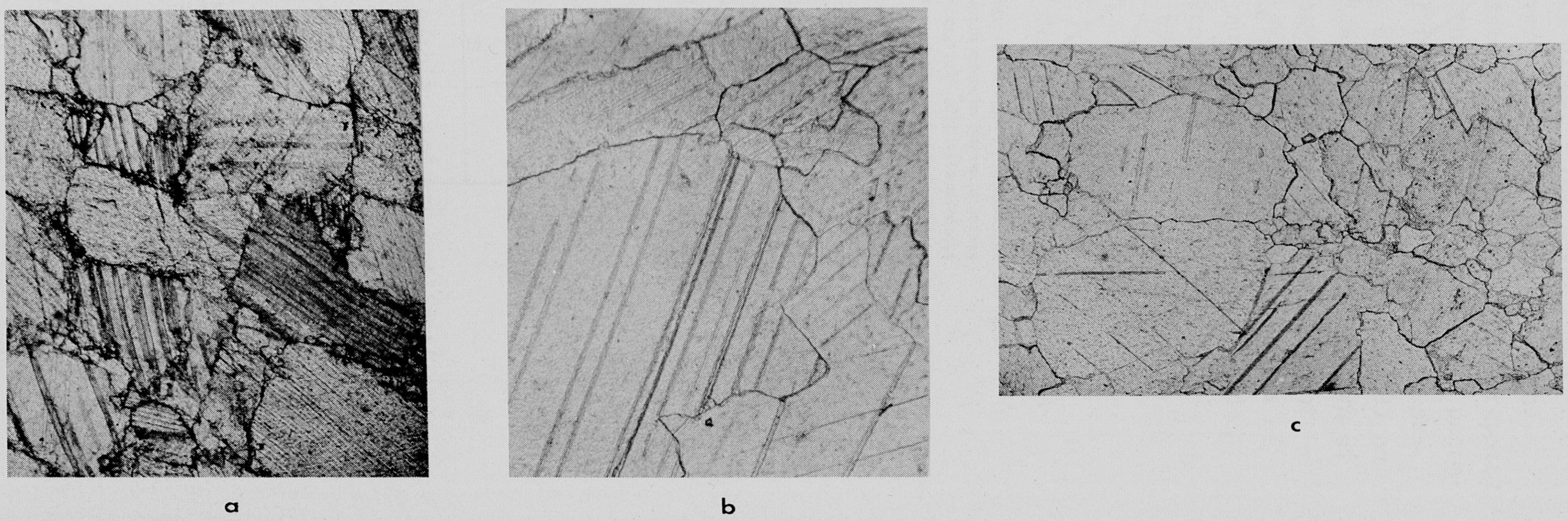

Plate 2. Thin sections of classic Greek marbles collected by N. Herz. Transmitted polarized light.
(a) Kos X 30
(b) Naxos X 85
(c) Paros X 30

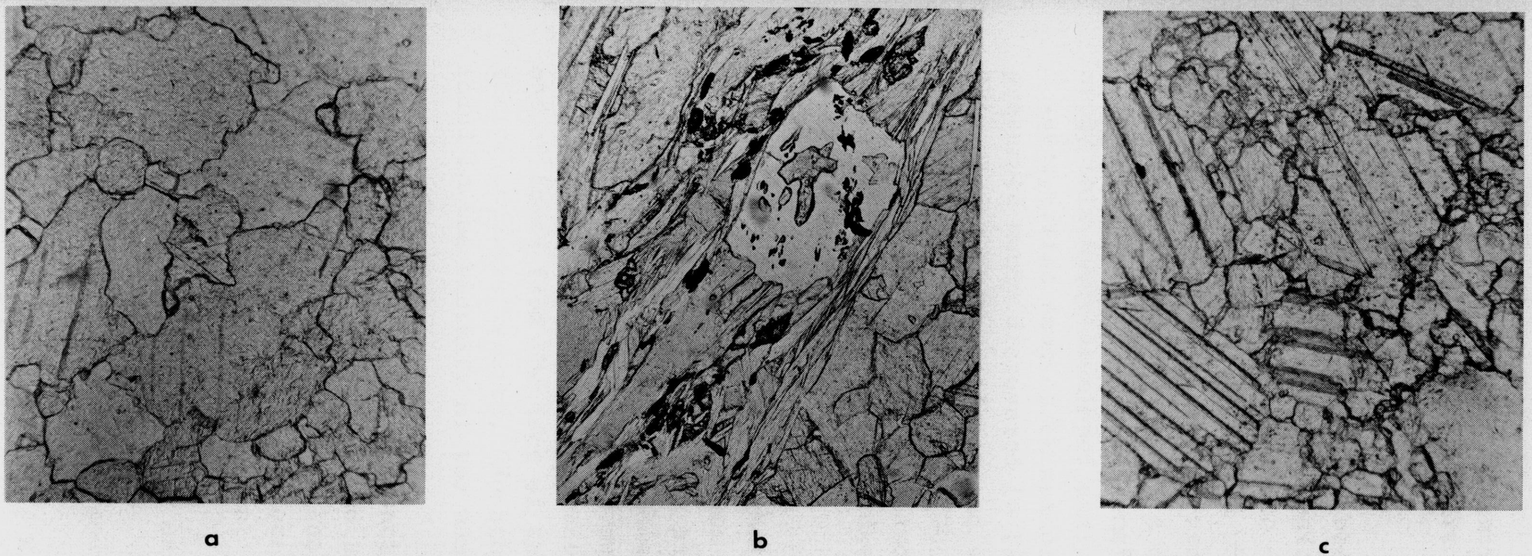

Plate 3. Thin sections of classic Greek marbles. Transmitted polarized light.

(a) Roman quarries Mt. Hymettus, Athens (N. Herz). X85

(b) Dionysus quarry Mt. Pentelicon (N. Herz); lower right half, calcite; upper left half, chlorite, albite epidote. X 30

(c) Temple of Sunion (said to be Pentellic). X 85

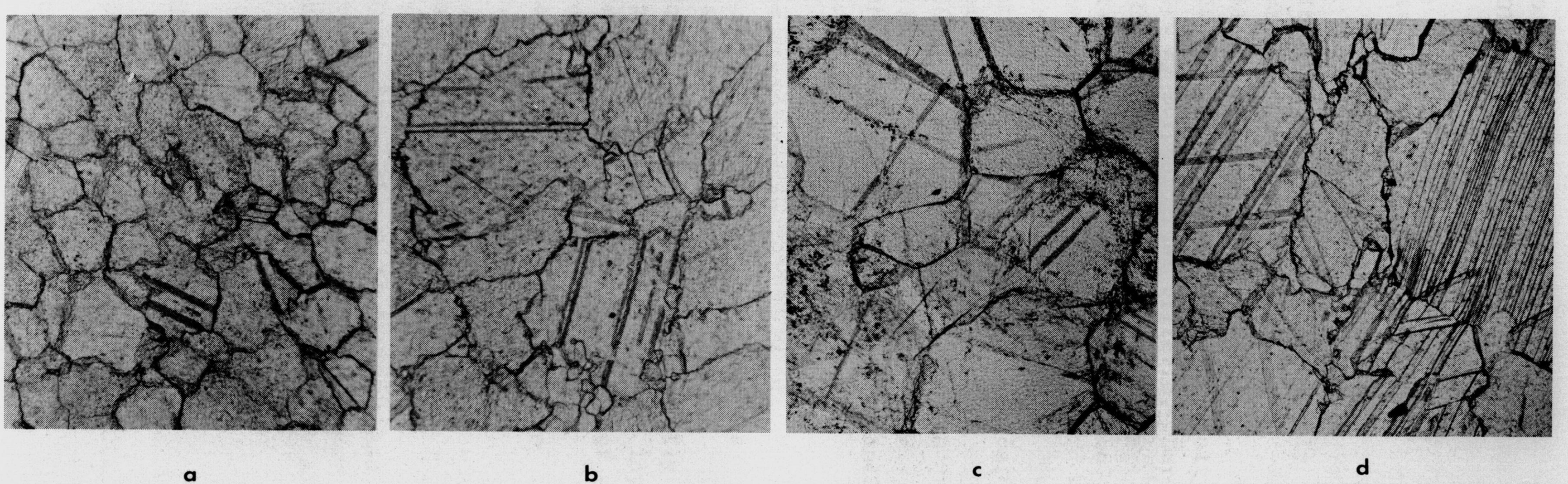

Plate 4. Thin sections of classic Italian marbles. Collected by author from modern quarries at old sites.

(a) Carrara X 85

(b) Carrara X 85

(c) Carrara X 30

(d) Lasa X 85