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MINERAL INTERGROWTHS REPLACED BY "ELBOW-TWINNED" RUTILE IN ALTERED ROCKS

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ABSTRACT

Some aggregates of rutile, classically considered to be "elbow" twinned, instead are topotactic replacements of ilmenite or other hexagonal titaniferous precursors. Twinned rutile can be differentiated from the reticulated rutile of topotactic replacements by the angle of prism intersections, junction morphology, and the overall form of the aggregate. In a special case of topotactic replacement of ilmenite, rutile forms pseudomorphs of "trellis"-textured ilmenite lamellae in {111} of precursor magnetite. We trace the progress of rutile formation through the alteration of fine-grained magnetite-bearing host rocks. The sequential two-step topotaxy from magnetite through ilmenite to rutile requires rutile prisms to parallel the intersections of {111} planes in precursor magnetite. Some coarse reticulated rutile may result from the same paragenetic sequence.

Keywords: rutile, elbow twin, topotaxy, trellis texture, ilmenite lamellae, hydrothermal alteration.

SOMMAIRE

Certains agrégats de rutile, considérés comme exemples classiques de macles "en genou", résultent au contraire d'un remplacement topotactique de l'ilménite, ou autre précurseur titanifère hexagonal. On parvient à distinguer les vraies macles de rutile de l'agencement réticulé des produits d'un remplacement topotactique par l'angle d'intersection des prismes, la morphologie de leur plan d'accolement, et la forme générale de l'agrégat. Dans un cas spécial de remplacement topotactique de l'ilménite, le rutile prend la place par pseudomorphose de lamelles d'ilménite à texture en treillis dans les plans {111} de la magnétite. Nous traçons le progrès dans la formation du rutile en examinant des roches à granulométrie fine porteuses de magnétite. La transformation en deux étapes de magnétite titanifère à ilménite et ensuite à rutile impose aux prismes de rutile un parallèlisme aux intersections des plans {111} de la magnétite originelle. Certains exemples de rutile à grains plus grossiers pourraient bien résulter de la même évolution paragénétique.

(Traduit par la Rédaction)

Mots-clés: rutile, macle "en genou", topotaxie, texture en treillis, lamelles d'ilménite, altération hydrothermale.

INTRODUCTION

Rutile commonly shows "elbow" (Hurlbut 1959) or geniculate (Palache *et al.* 1944) twins of its tetragonal prisms. However, some apparent elbow twins (Fig. 1) do not obey twin laws. In this article, 1) we document reticulated aggregates of rutile that topotactically replace ilmenite crystals in altered rocks, 2) we show that coarse aggregates of replacement origin are similar to some said to be elbow-twinned, and 3) we propose criteria to differentiate between twinning and topotaxy.

Twinned rutile crystals are most commonly contact twins on {101}, and the prisms of the twinned individuals intersect at 114°25′ (using a:c = 1:0.6442). Such twinning commonly is repeated, to form complete or incomplete cyclic or zig-zag aggregates, depending on the sequence of {101} planes involved in the twinning. Rutile also forms twins on {301}, though such twins are much less common, and usually involve only two individuals joined at an angle of 54°43′ across a single twin plane. Reticulate aggregates of rutile have been attributed to one or both of these laws.

Rutile forms regular intersecting arrays of prisms in other ways also. The simplest of these are epitactic or topotactic aggregates on or in certain host crystals (*cf.* Armbruster 1981). Ilmenite is the most common precursor. We here describe such aggregates, along with an interesting special case in which the ilmenite precursor is itself an array of exsolution lamellae in magnetite. In either case, alteration of precursor minerals produced aggregates of rutile with junctions that resemble elbow twinning, but that are actually growth features related only incidentally to twinning. [The term *sagenite*, commonly used for regular arrays of rutile crystals, has been used in conflicting ways (Armbruster 1981, Weibel *et al.* 1990), and we do not use it here.]

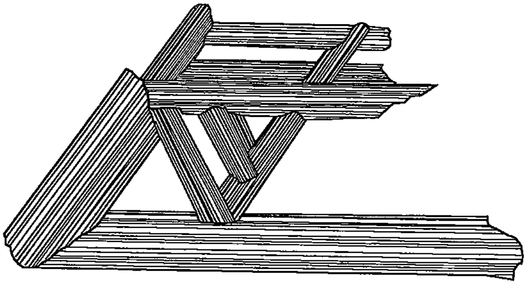

FIG. 1. Rutile aggregate considered by Ford (1932) and Hurlbut (1959) to be related to elbow twinning.

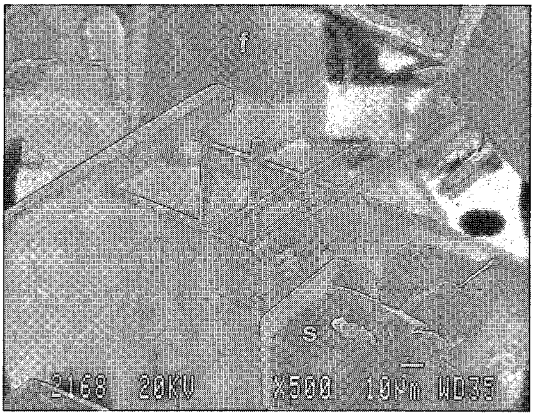

FIG. 2. Rutile pseudomorphic after hexagonal plates of ilmenite, hornfels from Mont Saint-Hilaire, Quebec, in scanning electron photomicrograph. Note rutile fingers projecting from the plate margins. Internally, the plate consists of platy prisms of rutile oriented in the three directions characteristic of rutile epitactic on ilmenite. Rutile occupies more than half the space of this ilmenite plate because titanium is somewhat mobile in the alkaline igneous environment, permitting the formation of overgrowths. Other phases visible are siderite (s) and potassium feldspar (f). Scale bar: 10 µm.

Rutile growth on ilmenite

Rutile is commonly epitactic on ilmenite (Armbruster 1981), or topotactic after ilmenite in altered rocks. Such growth is governed by the spacing and arrangement of oxygen atoms along the interface. The rhombohedral symmetry of ilmenite results in an array of rutile prisms lying on the basal plane of ilmenite that may intersect at 60° and 120° angles to form equilateral triangles (Fig. 2). The most common orientation is $\{010\}_{\mathrm{rut}}$ parallel to $\{0001\}_{\mathrm{ilm}}$, with $[001]_{\mathrm{rut}}$ parallel to $[21.0]_{\mathrm{ilm}}$. Armbruster listed several other orientations based on synthetic analogues of rutile and ilmenite; we find that these orientations differ from the ideal by 3° or less.

These aggregates epitactic on ilmenite are planar, and consist of approximately equal volumes of rutile and open space unless overgrowth occurs (Fig. 2). Topotactic replacement by rutile of ilmenite plates of appreciable thickness produces stacked planes of rutile aggregates that do not have a definite three-dimensional form.

Fine-grained rutile after trellis-textured ilmenite

A special case of epitactic–topotactic growth of rutile on ilmenite is the replacement of exsolution lamellae of ilmenite in magnetite. We find that rutile in this case inherits some distribution features from the three-dimensional form of the ilmenite lamellae themselves, because the mobility of Ti is normally minimal.

Igneous hosts

Rutile as a product of pseudomorphic oxidation of Fe–Ti oxide minerals has been thoroughly described from deuterically altered igneous rocks (*cf.* Haggerty 1976a, b, 1991). Primary igneous Ti-bearing magnetite exsolves an ulvöspinel (Fe_2TiO_4) component as it cools, which generally oxidizes to ilmenite–hematite. The resulting lamellae of ilmenite parallel the {111} planes of the magnetite host to form a so-called trellis texture (Fig. 3). In sections parallel to any octahedron face, the lamellae intersect at 60°; random sections show modified angles. Single-crystal study has shown that $(0001)_{ilm}$ parallels the $\{111\}_{mag}$, with $[11.0]_{ilm}$ parallel to $[110]_{mag}$ (Bernal *et al.* 1957). The magnetite {111} planes and thus the ilmenite lamellae intersect at angles of 70°32′ (or 109°28′). Usually, each of four orientations of {111} shows a set of lamellae, each with its own extinction direction in crossed polarizers. In some examples, ilmenite lamellae occupy only one orientation of {111}. Gradations between these "sandwich" intergrowths and trellis textures are characterized by a stronger development of lamellae in one orientation of {111} (Haggerty 1976a, Figs. Hg1f, Hg3d).

In pseudomorphic oxidation of Haggerty (1976a, b, 1991), trellis-textured magnetite–ilmenite alters deuterically to rutile and hematite (Fig. 4A), or pseudobrookite and hematite (Fig. 4B), with rutile and pseudobrookite occupying the positions of former ilmenite lamellae. The crystallographic controls on rutile in this iron-conserving process are not totally clear. In some altered igneous rocks, trellis-textured magnetite–ilmenite is replaced by titanium minerals other than rutile, such as titanite (Fig. 5), and iron minerals such as pyrite.

Hydrothermal alteration of igneous rocks in

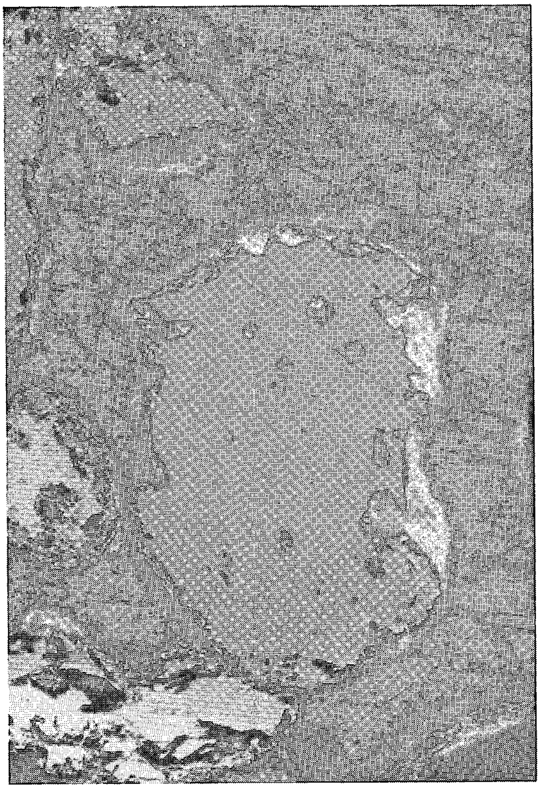

FIG. 3. Trellis-textured intergrowth of magnetite (darker) and ilmenite (brighter) in polished section of a little-altered grain of detrital sand from a modern Nile deposit (supplied by Jill Schneiderman).

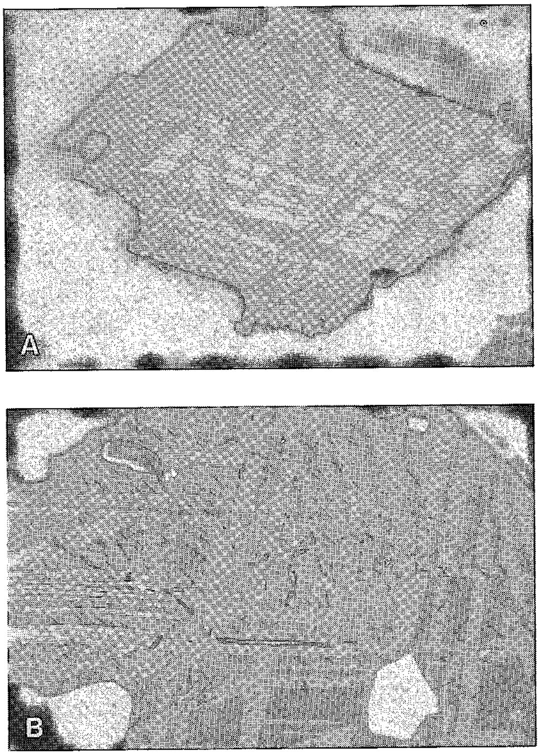

FIG. 4. Pseudomorphic oxidation of trellis-textured magnetite–ilmenite intergrowths of igneous rocks (supplied by Steven E. Haggerty). Reflected light; field of view: 0.35 mm. A. Pseudobrookite (darker) and hematite (brighter). B. Rutile and hematite (brighter, finely intergrown) together replace former ilmenite lamellae in magnetite and hercynite (darker).

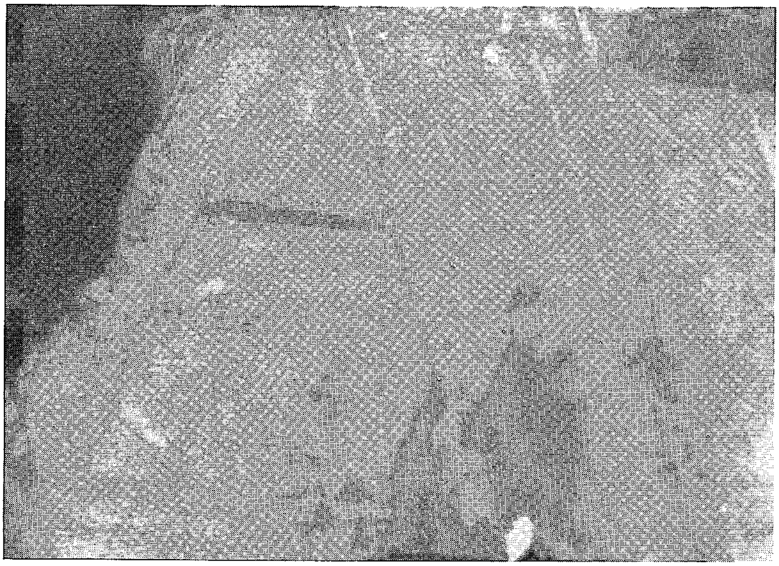

FIG. 5. Titanite pseudomorphic after trellis-textured ilmenite–magnetite intergrowth (supplied by Steven E. Haggerty). Reflected light; field of view: 0.35 mm.

porphyry copper (± gold) systems commonly produces reticulated aggregates of rutile if ilmenite–magnetite intergrowths occur in the parent rock. Ilmenite exsolved along {111} faces of magnetite is replaced by rutile as alteration proceeds; iron that is leached from ilmenite and the enclosing magnetite is incorporated into pyrite. In such rocks, rutile crystallites are thus oriented along the {111} faces of magnetite (Fig. 6). More highly altered rocks in the same progression may show additional overgrowth, giving more massive rutile but preserving triangular voids that represent the {111} faces of magnetite (Fig. 7).

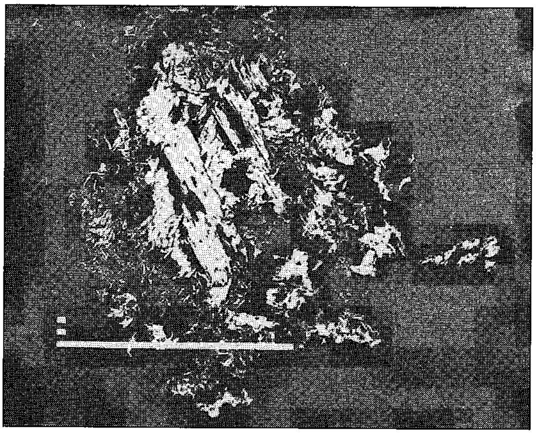

FIG. 6. Rutile pseudomorphic after a typical trellis-type ilmenite–magnetite intergrowth in propylitically altered Oracle Granite, Tucson Wash, Purcell (Kalamazoo) "window", San Manuel district, Arizona. Back-scattered electron image on electron microprobe; scale bar, 100 μm.

Sedimentary hosts

Descriptions of reticulated aggregates of fine-grained rutile in sedimentary rocks (Dimanche & Bartholomé 1976, Reynolds & Goldhaber 1978a, b, Fishman *et al.* 1985, Morad & Aldahan 1986, Figs. 9 and 16, Reynolds *et al.* 1986, Fig. 3, Turner-Peterson & Fishman, 1986, Figs. 8, 9, Valentine & Commeau 1990, Fig. 3, and Commeau & Valentine 1991, Fig. 1J) are found in the literature of sedimentary petrology and economic geology, but not in the mineralogical literature. Unlike igneous rocks, mineral phases intergrown with rutile in sedimentary rocks are commonly leached out without rutile overgrowth, so that the three-dimensional relations of rutile prisms can be seen.

In the studies listed, the authors attribute the presence of rutile to replacement of precursor iron–titanium oxide minerals, on the basis of three lines of evidence. First, fine aggregates of rutile correspond spatially to areas where detrital iron–titanium oxides have been altered and leached. Such alteration is associated with sandstone-hosted deposits of uranium (Fig. 8; Reynolds & Goldhaber 1978b, Fishman *et al.* 1985), stratabound copper deposits (Dimanche & Bartholomé 1976), and altered pyrite–gold placer deposits (Ramdohr 1958). Second, some precursor

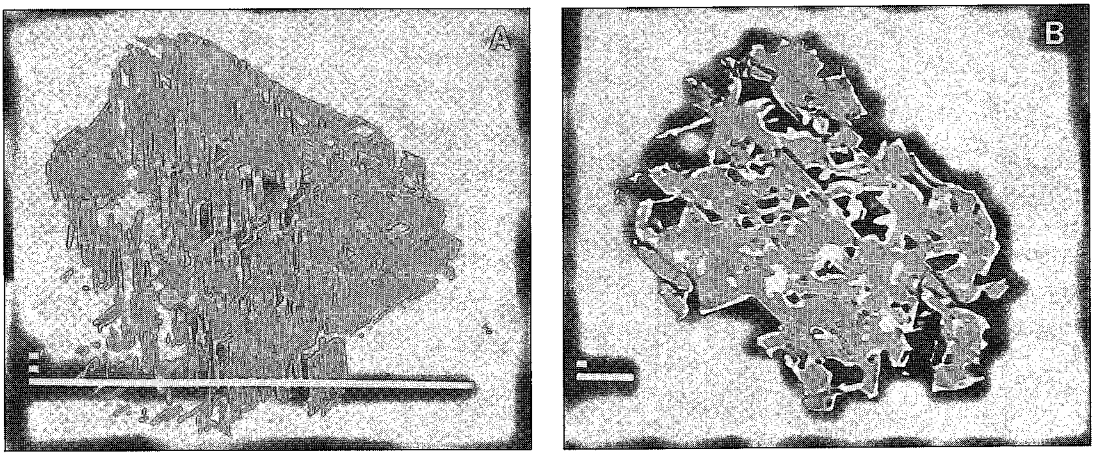

FIG. 7. Rutile from porphyry-related gold–copper deposits of northeastern Queensland (Australia), showing gradations from trellis texture to massive rutile with triangular voids. Back-scattered electron images. A. Ore zone of Kidston deposit; scale bar: 100 µm. B. Phyllic zone around Mount Leyshon deposit; scale bar: 10 µm. In these highly altered and mineralized environments, iron, tungsten, niobium, and vanadium may be incorporated into rutile (bright areas).

grains show incomplete replacement (Reynolds & Goldhaber 1978a, Reynolds *et al.* 1986, Mathis & Sclar 1982) to hematite and several Ti-enriched phases. Third, the array of rutile crystals shows a fixed geometric relation to textures of iron–titanium oxide minerals. Correlation of features between adjacent fresh and altered sandstone bodies shows that trellis-textured magnetite–ilmenite intergrowths are replaced by rutile in such a way that the trellis texture is preserved in three dimensions.

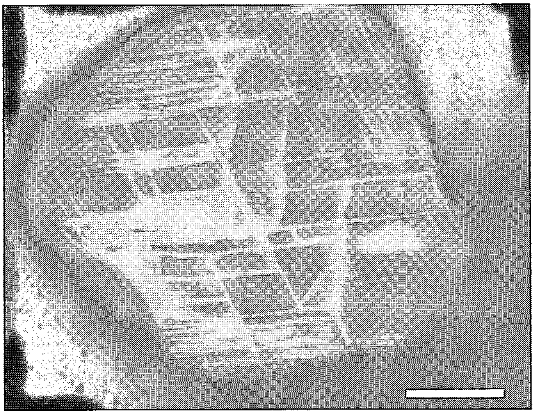

FIG. 8. Rutile in polished section of altered sandstone, Westwater Canyon Member of the Morrison Formation (Jurassic), San Juan Basin, New Mexico. Rutile (white) has replaced the planar former lamellae of ilmenite in detrital titaniferous magnetite, producing a trellis pattern with a discernible third dimension. Iron was removed during low-temperature diagenetic alteration, concurrently with the formation of uranium deposits. Vertically reflected light in oil; scale bar: 50 µm.

As in igneous hosts, titanium minerals other than rutile may form trellis-like intergrowths after iron–titanium oxide minerals. In sedimentary hosts, anatase (Reynolds & Goldhaber 1978a) and titanite most commonly show such intergrowths, locally with various iron minerals. These occurrences show that the texture of the rutile aggregates is a function not only of the crystallography of rutile but also that of precursor minerals.

We observe in aggregates of fine-grained reticulated rutile that prisms in a single plane intersect at 60° or 120° (not 114°25′, 54°43′, or their supplements, as necessary for twinning), that is, they form an array of equilateral triangles (Fig. 9A). Where three-dimensional relations can be observed, other planes rising at steep angles from the basal plane consist of parallel prisms (Figs. 9B, C). Intersecting prisms are generally stacked on each other with slight interpenetration (Figs. 9C, D).

Two of these features are analogous to the construction of a log cabin: the presence of wall planes in which each prism is parallel to the plane of the floor or basal plane (Fig. 9D), and the stacking with slight interpenetration of prisms at the corners of walls (Fig. 10). Henceforth, *wall* and *floor* planes are used as a shorthand notation. Note, however, that the "cabin" has prisms through its interior space, three prism orientations in its floor, and three walls not square with the floor, *i.e.*, the walls form an elongate pyramid. The

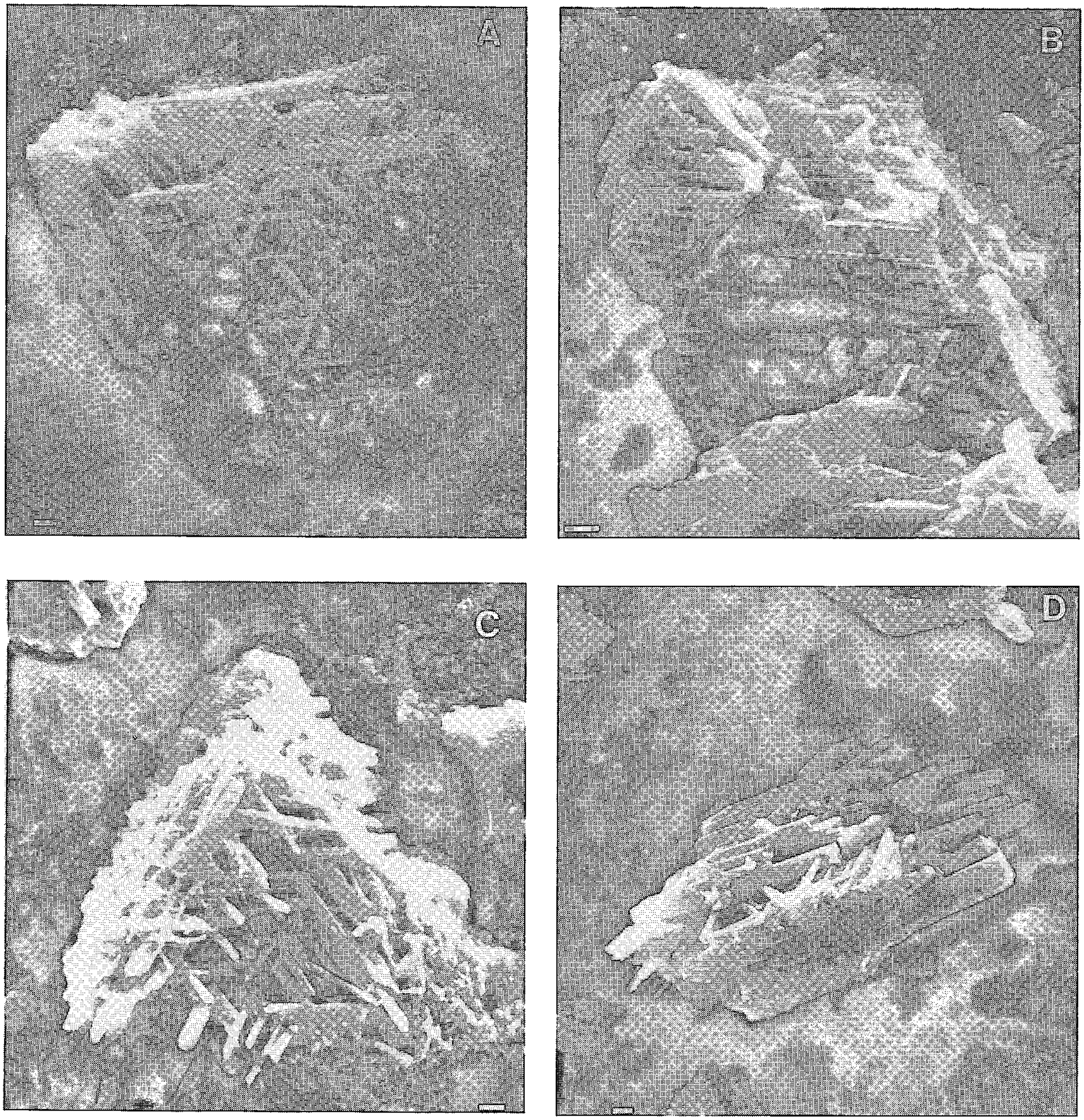

FIG. 9. Trellis-textured fine-grained rutile in sedimentary rocks, from scanning electron photomicrographs. A. Reticulated or trellis habit forming equilateral triangles in sandstone, Cumberland Group (Carboniferous) of Nova Scotia. B. Lath-shaped crystals of rutile replacing lamellae of ilmenite, extending into a pyramid-shaped trellis aggregate in sandstone of the Wolfville Formation (Triassic) of Nova Scotia. C. "Log cabin"-style stacking of rutile prisms within trellis aggregate, and pyramidal shape of the whole aggregate in the Cody Formation (Cretaceous) of Wyoming. D. Side view of trellis-textured aggregates of rutile, showing parallel prisms in "wall" planes and stacking style at corners, Cody Formation (Cretaceous) of Wyoming. Scale bar: 1 µm.

prisms are most commonly not equant in cross section, but elliptical or lath-like (Fig. 9B; see also Morad & Aldahan 1986, Fig. 9), such that their long dimensions in cross section are also at a high angle to the floor plane, and parallel to wall planes.

Relation of morphological and crystallographic aspects of trellis-textured rutile

The apparent descent of trellis-textured rutile from a magnetite–ilmenite precursor implies a two-step

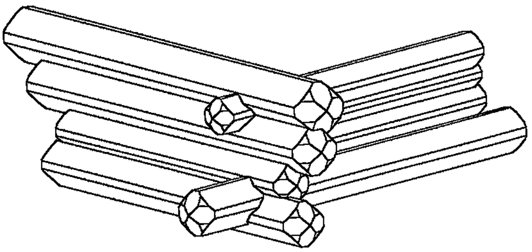

FIG. 10. Diagram of "log-cabin"-like intersections of rutile prisms that result from topotactic replacement. In the case of replacement of ilmenite lamellae in a magnetite host, the "walls" intersect at 60° and 120°, and rise from the floor at about 70° and 110°.

topotactic relation (magnetite–ilmenite and ilmenite–rutile) that correctly predicts the observed orientation of rutile in the floor plane. The most appropriate magnetite–ilmenite relation appears to be that of Bernal *et al.* (1957), who recorded the relation in exsolution lamellae. The epitactic relations of rutile on ilmenite listed by Armbruster (1981) all broadly satisfy the geometric requirements, but his relation IV in particular ($\{010\}_{rut}$ parallel to $\{0001\}_{hem}$; $[001]_{rut}$ parallel to $[21.0]_{hem}$), in tandem with the Bernal relation, results in rutile prisms aligned exactly parallel to the octahedron edges of magnetite, *i.e.*, parallel to the loci of intersecting {111} planes, as observed in trellis-like aggregates of rutile.

The observation that rutile prisms in the walls are all oriented parallel to the floor is crystallographically enigmatic, because the prisms occur in only one of the three equivalent orientations of the ilmenite lamella that was the precursor for the wall. A possible explanation is offered by the nature of the precursor lamellae of ilmenite; gradations between sandwich and trellis-textured intergrowths result in one dominant {111} plane containing most of the titanium, which would become the floor plane of trellis-textured rutile; subsidiary {111} lamellae would control the distribution of the wall planes without necessarily controlling prism orientation. The resulting framework of rutile crystals is commonly observed as nearly two-dimensional triangular aggregates in grain mounts; the wall planes are weak because the prisms are parallel there, so they probably break in such a way that the floor planes remain intact.

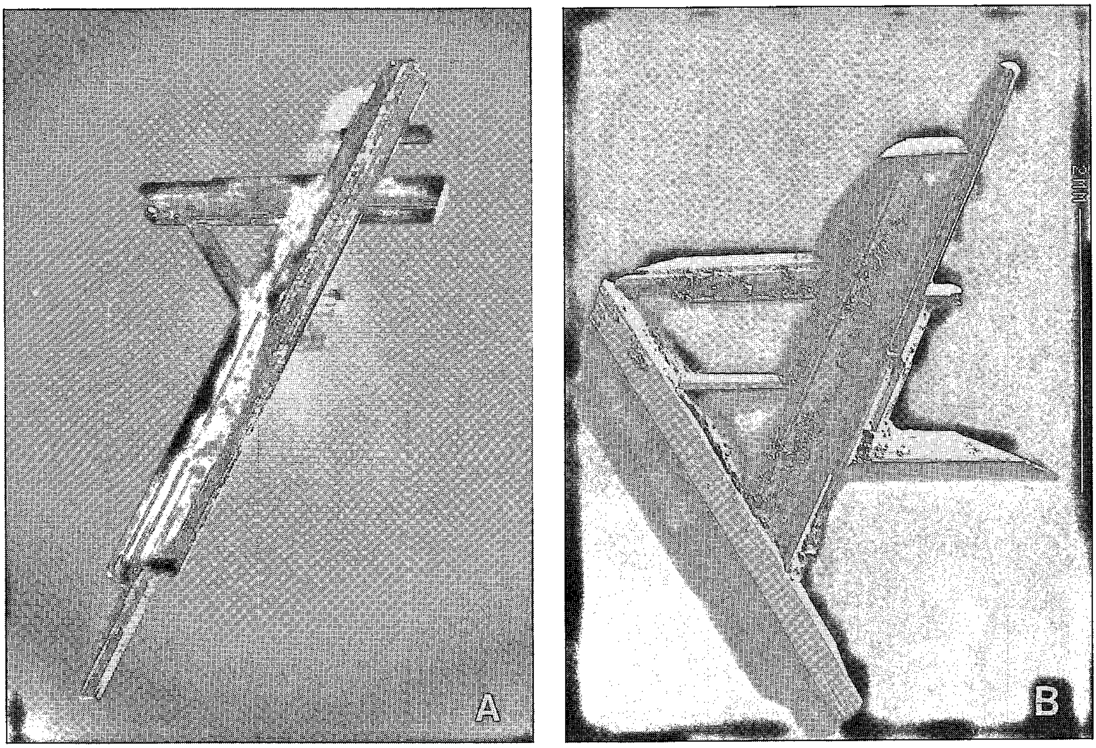

FIG. 11. Coarse aggregates of rutile in kaolinized green-beryl, green-spodumene granitic pegmatite near Stony Point, North Carolina. Note that adjacent prisms are not truly coplanar but are stacked with slight penetration. A. Transmitted and reflected light; field of view: 0.5 cm. B. Scanning electron micrograph; scale bar: 2 mm.

Reticulated aggregates of coarse-grained rutile

Some coarse-grained aggregates of rutile are geometrically similar to those described above from fine-grained aggregates, but are also similar to those that have been ascribed to elbow twinning (Fig. 1). We find that some aggregates result from epitactic–topotactic growth on ilmenite or other hexagonal precursor, that others probably involve replacement of ilmenite lamellae in magnetite or another octahedral host, but that reticulated aggregates of rutile involve twinning only incidentally.

For example, we studied some aggregates of rutile crystals (Fig. 11) collected in the last century by W.E. Hidden from a kaolinized body of beryl–spodumene pegmatite (Smith 1881) in biotite gneiss and (greisenized?) mica schist near Stony Point, Alexander County, North Carolina. As in the fine-grained aggregates, prism intersections are at 60° ± 2° or 120° ' 2° in floor planes (Fig. 11). Wall planes containing a few parallel prisms rise from floor planes at steep angles (not shown: difficult to photograph). Wall corners contain slightly interpenetrating prisms, and some prisms are flattened in cross-section parallel to wall planes.

These relations are all consistent with replacement of ilmenite. We suggest but cannot prove that an octahedral host of ilmenite influenced the form of the aggregate, based on a few apparent features of wall planes, and the more open structure of this trellis structure in rutile as compared with that derived from solid ilmenite. Coarse-grained rutile would require coarse-grained precursor minerals, but coarse rutile from Stony Point is consistent with its derivation from hydrothermally altered pegmatite.

In contrast, specimens apparently after coarse crystals of ilmenite without a magnetite precursor (such as those from near the Lineboy prospect of the Patagonia Mountains, Arizona) have rutile prisms forming equilateral triangular arrays in each of a succession of tightly packed planes, but there is no relation among planes that gives the aggregate a three-dimensional structure. In other respects, such aggregates closely resemble those from Stony Point and the finer rutile of Figure 9, and the distinction between the two types of precursor is not trivial.

CRITERIA TO DISTINGUISH TWINNING FROM TOPOTACTIC REPLACEMENT

A number of criteria (Table 1) help distinguish between reticulate rutile that results from twinning and from topotactic replacement. Some of these distinctions may be obscured by secondary overgrowths; some apply to early-formed junctions but not to late ones. Twinning may occur coincidentally during topotactic replacement. Thus a "weight of evidence" approach is appropriate in applying these criteria.

TABLE 1. DISCRIMINATION BETWEEN FEATURES OF TWINNING AND TOPOTAXY IN RUTILE INTERGROWTHS

Twinning	Topotaxy	
	Simple on hexagonal host	Sequential octahedral – hexagonal hosts
Angles are 114°25' (most common), 54°23', or their supplements at twin junctions; other angles at impingement junctions	Angles of 60° and 120° in planar array	Angles of 60° and 120° in floor plane; 70° or 110° between floor and wall planes
Overall form stochastic	Overall form hexagonal	Overall form reflects octahedral distribution of hexagonal lamellae
Crystal cross sections like non–reticulate rutile	Crystals may be flattened in plane of aggregate	Crystals commonly flattened in floor and wall planes
Branching in non–coplanar directions	Branching confined to a plane	Branching confined to {111}; empirically in one plane
Multiple aggregates randomly oriented	Multiple aggregates share common orientation	Multiple aggregates share common orientation
Twinned junctions strong, not offset	Junctions by impingement, joints weak and offset	Junctions by impingement, joints weak and offset
Kinked steps common	Kinked steps rare or absent	Kinked steps rare or absent
Ribbon–like prism faces continuous across twinned junctions	Ribbon–like prism faces interrupted at all junctions	Ribbon–like prism faces interrupted at all junctions

Topotaxy

Replacement of ilmenite by rutile occurs according to the well-known epitactic relationship $\{010\}\ [101]_{\mathrm{rut}}$ $\{0001\}\ [21.0]_{\mathrm{ilm}}$. It is likely to begin with nucleation of rutile crystals or aggregates of crystals at multiple sites in or on the same crystal of ilmenite, with rutile crystals oriented in one or more of the three equivalent [21.0] directions in {0001}, which lie at 120° to each other. Further growth of the elongate crystals will lead them to impinge on each other, forming noncrystallographic junctions that make angles of 60° and 120°, *i.e.*, simulating twinning but with the wrong angles (Table 1). Most of these junctions will involve individuals of somewhat different sizes and offset centers (Figs. 1, 9, 10, 11). Junctions may be Y-shaped if one crystal's growth is halted by impingement. In some cases, crystals may grow past each other and only merge as the prisms thicken with further growth, to form X-shaped junctions (Figs. 1, 9, 10, 11). Because the junctions are noncrystallographic, they are likely to be relatively weak and to involve irregular composition-surfaces, in contrast to the strong, planar junctions that result from twinning.

Energetic advantages conferred by the epitactic relationship may cause the crystals to grow more rapidly parallel to {0001} of ilmenite than in other directions, and to form crystals with a platy morphology (Figs. 2, 9B). If multiple orientations of ilmenite lamellae are present, flattening may occur parallel to each. Growth of the rutile aggregate is likely to be governed by topotactic replacement, resulting in a reticulated aggregate of rutile whose overall form is that of the ilmenite crystal it replaces.

Twinning

Growth twins of rutile usually involve individuals of about equal size in contact with each other across a planar composition-surface. Where the zone of faces parallel to the *c* axis is complex, showing ribbon-like striations (resulting from oscillatory growth of different faces of {100} or {110}), these striations continue across the composition surface without interruption except for the kinking imposed by twinning. Twin junctions are nearly as strong as equivalent sections through untwinned crystals. Twinning occurs on {101} and, less commonly, on {301}, leading to prism-intersection angles of 114°25′ and 54°43′, respectively.

Typical junctions formed by twinning in rutile are simple kinks, whereas Y-shaped or X-shaped junctions are required to form a reticulated network. X-shaped junctions could result from penetration twinning, but such twinning of rutile has not been described. Y-shaped junctions could form by twinning if a pre-existing crystal twinned during further growth along the prism; the resulting budded crystal would be smaller than the original crystal.

In this "bud twinning" model, a new bud could branch with equal probability in any of the eight directions corresponding to [101]. Thus an aggregate formed by twinning should branch in three dimensions, forming an overall shape governed primarily by the balance between growth rate and budding frequency. Some extra constraint would be required to confine the branching to planes, even the four planes common in some of the reticulated aggregates of rutile we describe. If bud-twinned aggregates intersected, impingement junctions could be expected with a large variety of angles, in contrast to the regular angles of impingement junctions formed by topotactic replacement.

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