Plagioclase twins in some mafic gneisses from Broken Hill, Australia

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Summary. Plagioclase in mafic gneisses from Broken Hill, Australia, contains twins that can be divided into two groups on the basis of shape: firstly, lamellar twins that gradually change thickness across a grain or form lenticular terminations; and secondly, simple and lamellar twins that show angular steps in the twin interface or form abrupt, planar terminations. The former are interpreted as mechanical twins, and the latter as growth twins formed by grain growth in the solid state, arguing largely by analogy with twin shapes in experimentally produced aggregates, particularly metals. The only twin laws observed in lenticular twins are albite and pericline, these being of nearly equal abundance. Stepped twins are much less common than lenticular twins, and in rocks without lenticular twins most of the plagioclase is untwinned. Several twin laws occur among the stepped twins, but the albite law is the most common. Simple twins on the albite and albite-carlsbad laws are prominent.

THE mafic gneisses occurring around Broken Hill, New South Wales, are relatively coarse-grained (0·5–1·5 mm), granoblastic rocks consisting mainly of calcic plagioclase (bytownite), clinopyroxene, orthopyroxene, and brown hornblende, as described by Browne (1922), Stillwell (1922), Edwards (1958), and Binns (1962). The plagioclase contains twins large enough for detailed observation of their shapes with the universal stage, which is the primary aim of this investigation. An attempt has also been made to correlate shape with mode of origin and with twin laws.

The observed twins can be divided into two groups on the basis of shape: firstly, those lamellar twins that gradually change thickness across a grain or form lenticular terminations; and secondly, those simple and lamellar twins that show angular steps in the twin interface (composition plane) or form abrupt terminations. Each group will be described and discussed separately.

In most mafic gneisses examined, the great majority of the plagioclase grains are twinned, with lenticular twins well in excess of stepped twins; twin frequencies for such rocks are given in table I. However, a few

rocks contain largely untwinned plagioclase, lenticular twins being rare and minute; stepped twins occur in approximately 10 % of the plagioclase grains in such rocks, and an analysis of these twins is given in table II.

TABLE I. Plagioclase twins in typical mafic gneisses from Broken Hill, N.S.W.

Twin law		Pericline	Albite	Carlsbad	Albite-carlsbad	Manebach-ala or Acline	Manebach
Grains with lenticular twins (total 88)		42	46	—	—	—	—
Grains with stepped twins (total 36)	Simple	—	7	6	5	1	1
	Lamellar	—	14	—	1	1	—

TABLE II. Stepped twins in plagioclase of mafic gneisses without lenticular twins

Twin law	Albite	Carlsbad	Albite-carlsbad	Manebach-ala or Acline
Grains with simple twins (total 30)	21	4	4	1
Grains with lamellar twins (total 24)	19	—	4	1

Lenticular twins

Shape. Many plagioclase grains show abundant lamellar twins that gradually alter thickness across the grains (fig. 1 A and B). Generally the change in width is marked, so that the twins are wedge-shaped or lenticular, but some twins appear to be of regular width at low magnification, although closer observation reveals some swelling and pinching of the lamellae. These features are in marked contrast to the straight interfaces and planar, angular steps of the second group of twins described below.

Most lenticular twins cross whole grains, but some terminate within grains, generally against lamellae of another twin law; the terminating twin tapers to a minimum thickness against the other twin (fig. 1A). However, occasional twins terminate within apparently homogeneous parts of grains, and these taper gradually to extremely fine points, so much so that the actual terminations are imperceptible, even at a magnification of 800 diameters.

Some grains contain as many as 50 lenticular lamellae as thin as 0·001 mm and even less, whereas other grains contain as few as three lamellae, which may be as thick as 0·3 mm at their widest parts. Where
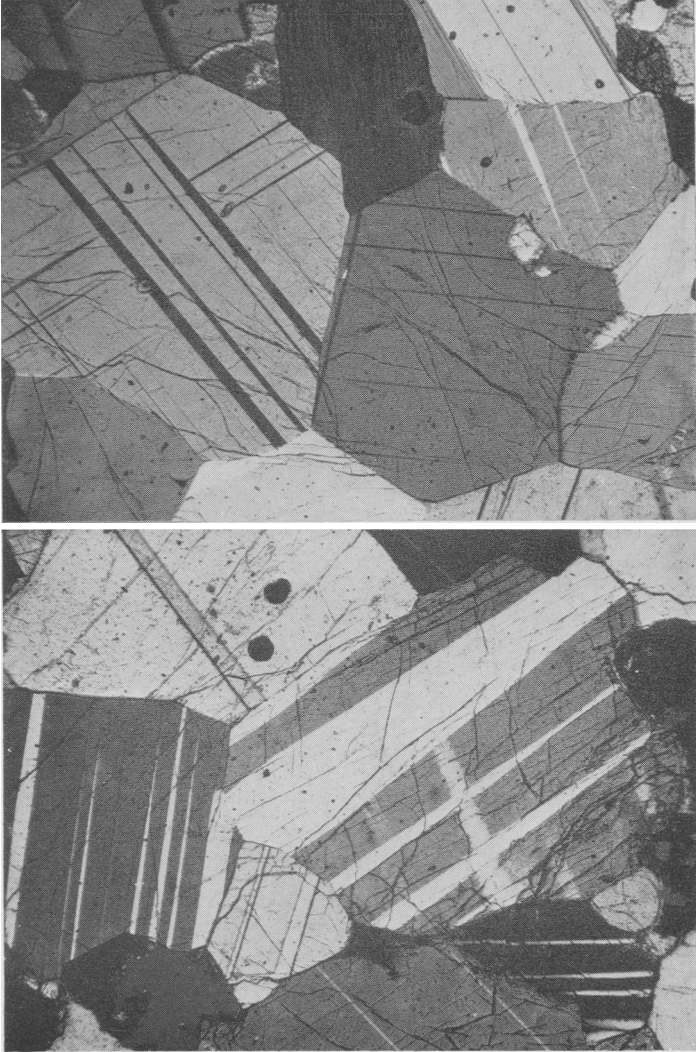
FIG. 1. A (top): Polygonal grains of plagioclase showing lenticular twins. In the left-hand grain several pericline lamellae can be seen tapering into the composition plane of a large albite twin, and several very thin albite lamellae taper into the pericline lamellae. ×30. B (bottom): Typical lenticular twins, most of which continue right across grains, although a few albite twins in the left-hand grain appear to terminate internally. Note the particularly wide pericline lamella. ×30.

lenticular twins encounter plagioclase–plagioclase grain boundaries, the latter generally appear to be deflected, as illustrated in fig. 1B. However, the nature and amount of deflection are variable.

The only twin laws observed[1] in lenticular twins are the albite and pericline laws (table I), some grains showing one law, others both. Where twins of both laws are present, they must intersect or impinge on one another. Generally one twin tapers into another without reappearing on the other side (fig. 1A); this is especially so where the impinging lamella is much thinner than the other. Where the earlier-formed twin is relatively thick, lamellae of the second law may be formed within it (figs. 3, 4). Areas of undulose extinction, suggesting lattice strain, surround the points of impingement of some twins (fig. 2B, c), but generally such evidence of strain is not apparent. Many albite–pericline twin intersections occur, in which one twin appears, at low magnification, to pass through and displace the other, without tapering into the intersection. However, observation at high magnification reveals areas of undulose extinction at the intersection. This strained area actually extends beyond the intersection itself, in the form of a thickened zone bounded by planar interfaces, as shown in fig. 2. These intersections are common where the twins are of similar thickness and where the second twin is thicker than the first. Some intersections are very complex, several small twins emanating from the intersection zone (fig. 3). These observed features of albite–pericline twin intersections will be discussed later from a theoretical viewpoint.

Origin. The shapes of the lenticular twins are identical to those of *mechanical* (deformation, glide) *twins* in metal aggregates (e.g. α-iron, tin, zinc, cadmium, and uranium), as described and illustrated by many writers, including Mathewson (1928), Jillson (1950), Cahn (1953, 1954), Pratt (1953), and Hall (1954). They also resemble mechanical twins produced experimentally in calcite, as illustrated by Turner, Griggs, and Heard (1954, p. 922, fig. 23). Thus the lenticular twins may have had a similar origin by deformation, although more experiments will be necessary to prove this. Mechanical twins in plagioclase have been produced experimentally by Mügge and Heide (1931), Buerger (1945), and Borg, Handin, and Higgs (1959), although no photomicrographs of the twins were published. Vance (1961) and Seifert (1964) have presented criteria for the recognition of apparent deformation twins in plagioclase.

The mode of formation of mechanical twins in metals has been

[1] Twin laws were determined with a four-axis universal stage by the method of Turner (1947).
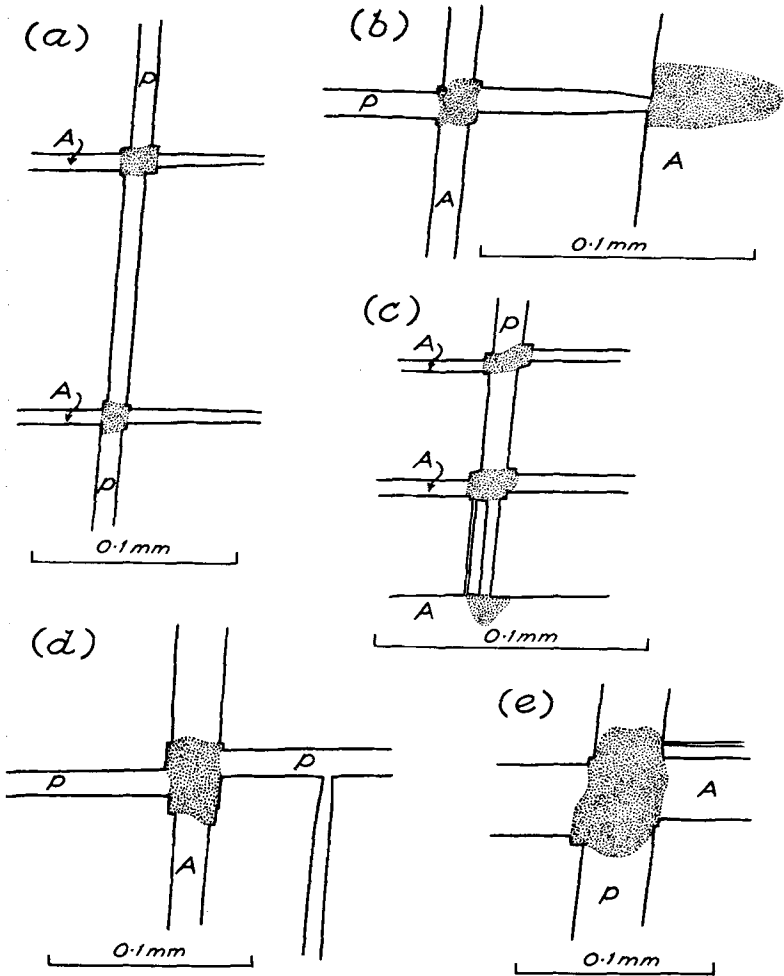
FIG. 2. Intersections of albite (A) and pericline (P) twins, showing the thickened zone bounded by plane steps, and the area of undulose extinction (stippled). In diagram A, the vertical twin is the earlier and is displaced, whereas in diagrams B to E, the horizontal twin is displaced. The later twin is either unchanged in thickness or is thinned (D); it may also become split into two lamellae (C). Diagram D shows both intersecting and abutting twins. Zones of undulose extinction occurring where pericline lamellae impinge on thick albite lamellae are shown in B and C.

investigated and reviewed by many workers, such as Mathewson (1928), Jillson (1950), Cahn (1953, 1954), and Hall (1954), so little would be gained by repeating the details here. As discussed by Cahn (1954), parallel interfaces in mechanical twins are theoretically probable in
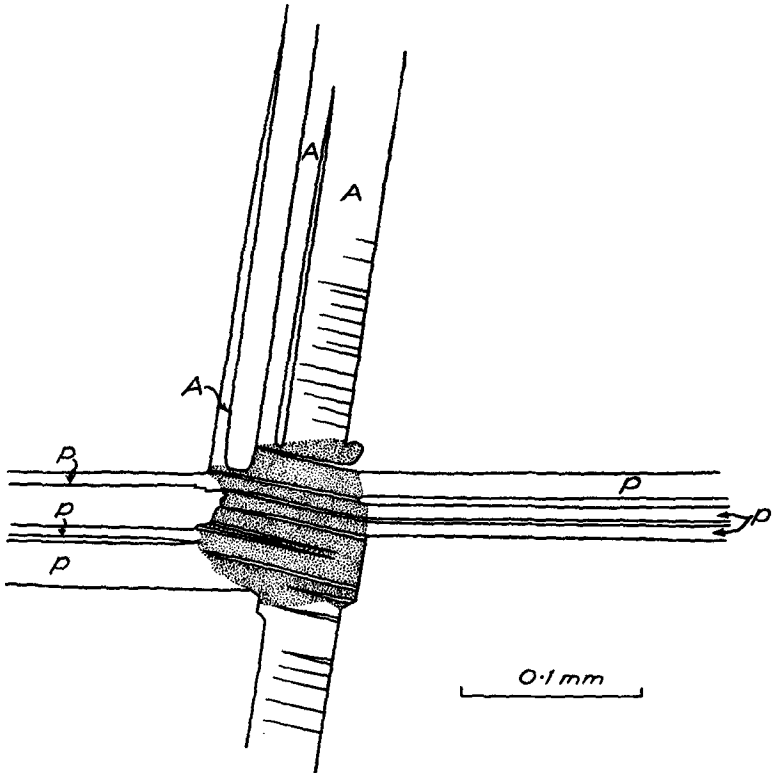

FIG. 3. Complex intersection of mechanical albite (A) and pericline (P) twins, showing zone of undulose extinction (stippled), and thin pericline lamellae within this zone and within the large albite twin.

single crystals, but in polycrystalline metal aggregates the interfaces typically taper, in an attempt to minimize lattice strains associated with twin terminations at grain and twin boundaries (Hall, 1954, pp. 64, 77). Therefore, although abrupt steps would be incompatible with an origin by shear, it appears that *gradual* changes of interface direction form a reliable criterion of mechanical twinning in polycrystalline aggregates.

Twin intersections. In metals an existing twin lamella generally acts as a barrier to a later deformation twin lamella operating on another law (glide system), as described by Cahn (1953, 1954) and Hall (1954). The new lamella either tapers to an abutment against the earlier one, or else appears to have generated a new lamella on the other side of the barrier by means of the impact shock transmitted through the early lamella.
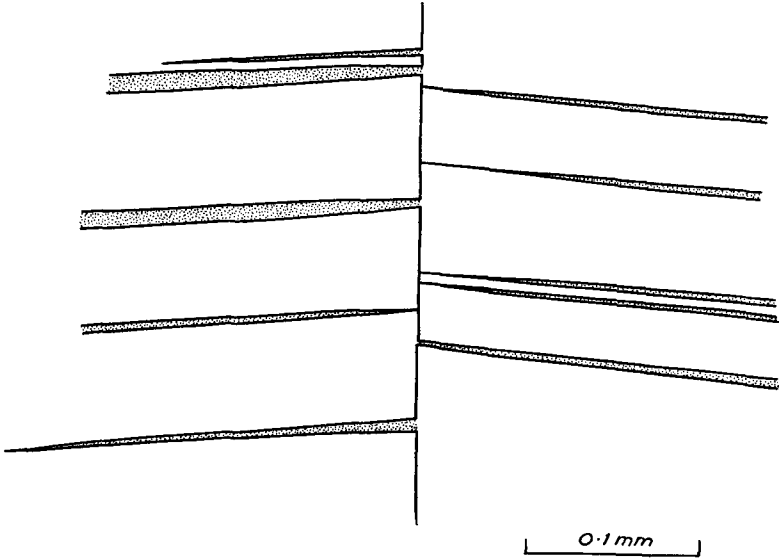

FIG. 4.　Thin pericline lamellae tapering into and away from an interface of a thick albite twin.

Such abutting lenticular twins are common in tin and zinc, as illustrated by Mathewson (1928, figs. 3, 4, 13, 14) and Hall (1954, figs. 47, 62), and very similar shapes are shown by abutting twins in the plagioclase of the Broken Hill mafic gneisses (fig. 1A).

Exceptionally in metals, the new lamella passes, without strain, through the first lamella by forming a secondary twin within it. Cahn (1953) has examined in detail the conditions necessary for mechanical twins on two laws to form such compatible intersections, concluding that the first lamella must be a twin with a rational composition plane, and that the shear direction operating in the crossing lamella must be parallel to the line of intersection of the two lamellae. The second condition is not fulfilled for intersections of albite and pericline twins, and

neither is the first condition where pericline twins are the first-formed lamellae. Moreover, the direction of shear would be slightly different inside and outside the crossed lamella, and the sense of shear would be reversed (fig. 5). This means that compatible, strain-free intersections of albite and pericline twins, with the formation of true secondary twins in the crossed lamellae, cannot occur.

However, as noted previously, intersections do occur, in which one lamella passes through another, displacing it slightly (fig. 2). The two lamellae are typically of similar thickness, and twins of either law are displaced by twins of the other. The intersecting twins do not taper into one another; instead, the intersection consists of an enlarged, strained zone bounded by apparently planar surfaces (fig. 2). These features appear roughly explicable by postulating one lamella (on either the albite or pericline law) being formed first, followed by the impact of the second lamella. If the first lamella is too wide, the second twin merely impinges on it, with or without the formation of a strained zone around the point of impact (figs. 2B, C, D, E). However, if the first lamella is thin enough, the second twin may force its way through, displacing the earlier twin, and continue on with either the same thickness as before (figs. 2B, E) or reduced thickness (figs. 2A, C, D). The writer cannot explain the enlarged zones with their angular steps, but they are strained areas, and would appear to have a deformational origin associated with the difficult act of twin-crossing. The complex intersections (fig. 3) presumably resulted from local stresses at the intersections; they resemble complex intersections of twins in zinc (Pratt, 1953, figs. 6, 7).

Donnay (1961) has pointed out that although the composition planes of albite and pericline twins are almost normal to each other, the orientations of the lattice in albite and pericline lamellae differ only slightly.[1] Perhaps this is what permits the observed twin-crossing, in the face of otherwise very unfavourable conditions.

Twin laws. The general geometry of mechanical twinning has been reviewed many times, for example, by Bell (1941), Cahn (1953, 1954), and Hall (1954). Mechanical twins involve a small amount (macroscopically) of simple shear in a direction parallel to the composition plane (glide plane). This implies that the composition plane must remain undistorted throughout the twinning operation, and thus provide a

[1] This is because albite twins may be thought of in terms of a lattice rotation of 180° about the exact normal to (010), and pericline twins involve a 180° rotation about the pseudonormal to (010), namely [010]; see fig. 4.
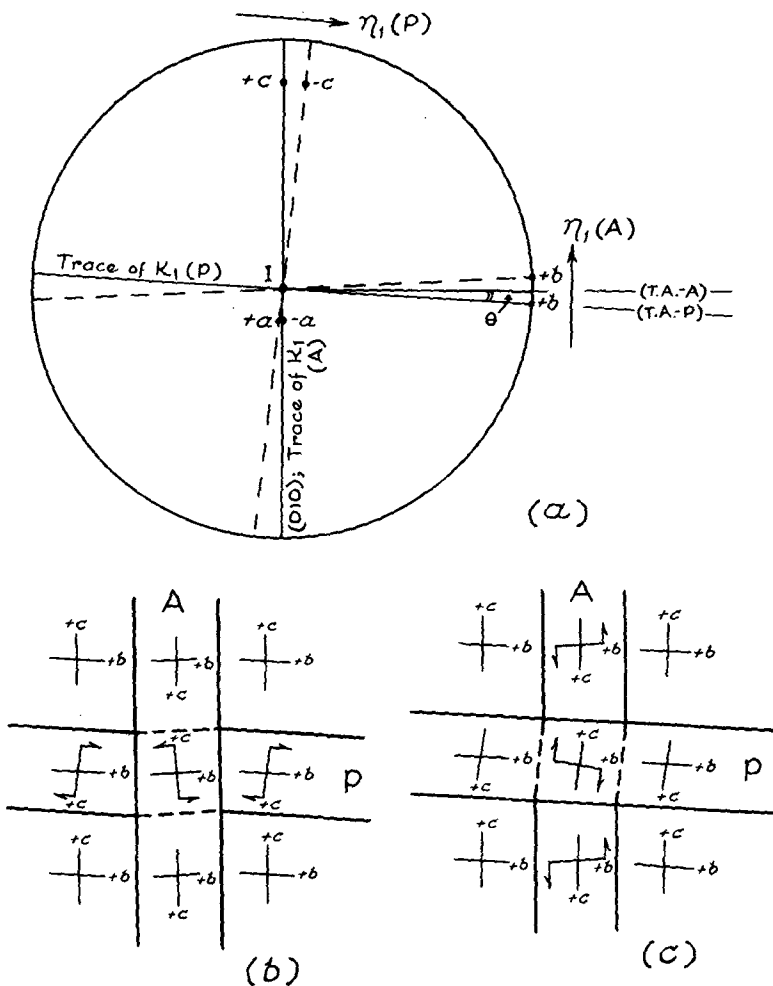
FIG. 5. (a) Stereographic projection (*lower* hemisphere) of bytownite, showing, in solid lines, the traces of the glide planes (K_1) and macroscopic glide directions (η_1) of mechanical twins on the albite (A) and pericline (P) laws. The diagram also shows, in dotted lines, the position of the glide plane of each law after twinning on the other law; $-a$ becomes $+a$, and $+c$ becomes $-c$, after twinning on the albite law, and $+b$ remains the same after twinning on the pericline law. The twin axes for albite twins (T.A.-A) and for pericline twins (T.A.-P) are also shown, as well as the obliquity (θ). Note that neither of the glide directions (η_1) coincides with the line of intersection (I) of albite and pericline twin lamellae.

(b) and (c). Diagrams illustrating hypothetical situations, in which albite (A) and pericline (P) twin lamellae are envisaged as forming compatible intersections. The reversal of the sense of shear in the crossed lamellae shows that the situation is impossible. In (b) the albite twin is the first-formed, whereas in (c) the pericline twin is the first-formed.

low-energy, coherent interface shared by both twin individuals. The amount of shear (s) is related to the angle (2ϕ) between the glide plane (K_1) and the other undistorted plane (K_2) by the expression: $s = 2 \cot 2\phi$; see fig. 6. In pseudomerohedral twins, s is related to the obliquity (θ) by the expression: $s = 2 \tan \theta$.

Twins on the albite and pericline laws are the most common natural examples of pseudomerohedral twins. They are representatives of Mügge's 'reciprocal twins', as shown by Pabst (1955, p. 899), and can be described in terms of a small amount of simple shear parallel to (010) for albite twins and parallel to the rhombic section for pericline twins (fig. 5). Both laws involve the same amount of shear, because both depend on the relative positions of (010) and [010]; i.e. on the obliquity.[1] Table I shows that mechanical albite and pericline twins are of nearly equal abundance in the Broken Hill mafic gneisses investigated in detail, as might be expected from the identical amounts of shear involved in each law.[2]

It appears that pericline twins must always be of mechanical origin, because their composition planes are irrational (Cahn, 1954). However, theoretical considerations do not preclude growth twins on any other plagioclase laws, provided the composition plane is rational.

Manebach twins would appear to require too much shear to form by deformation; they would involve a very large movement of [001] in a direction parallel to the composition plane (001). In plagioclase this would make $2\phi = 63° 26'$, $s = 1\cdot000$ for albite, and $2\phi = 64° 9'$, $s = 0\cdot969$ for anorthite, using values of β given by Deer, Howie, and Zussmann (1963, p. 94). However, mechanical twins with 2ϕ less than $70°$ are unknown (Cahn, 1954), so that Manebach twins should only occur as growth twins, such as those described by Seifert (1964).

The same restriction applies to the irrational-type, so-called 'estérel'

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[1] Theoretically, the obliquity affects the frequency of albite and pericline lamellae along the plagioclase series (Donnay, 1940), but very careful experiments would be needed to test this, and the effect may be overshadowed by energy differences involved in detailed atom movements and by external conditions. For albite and pericline twins, s varies from $0\cdot150$ for An_0 to $0\cdot135$ for An_{30-40} and back to $0\cdot151$ for An_{100}, using the obliquity and An values given by Gay (1956, p. 303).

[2] Borg, Handin, and Higgs (1959) suggested, as a result of some experiments, that the critical resolved shear stress for pericline twinning is about twice that for albite twinning. However, the sense of shear in pericline twinning is the reverse of that given by these writers, which means that their 'A' cylinders favoured the production of both twin laws, whereas 'B' cylinders favoured neither law. This explains the much greater strength of 'B' cylinders, so that the postulated difference in critical resolved shear stress must be regarded as unproved. This conclusion has been verified by Dr. Borg (personal communication, 1964).
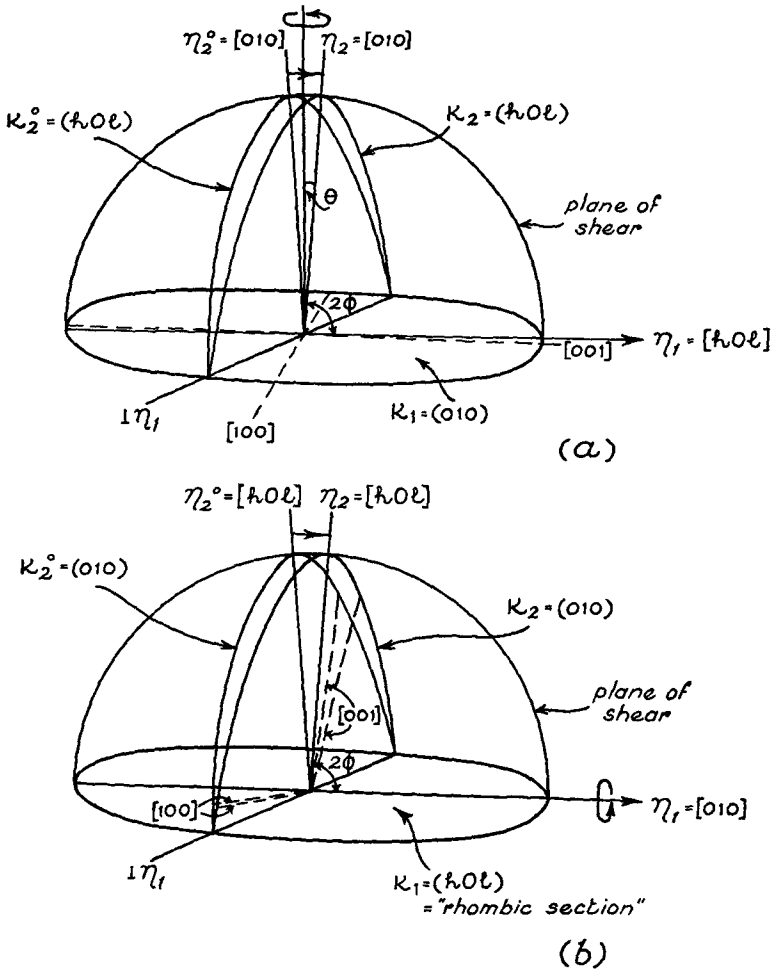
FIG. 6. Diagrammatic representation of macroscopic shear movements involved in the formation of (a) *albite* and (b) *pericline* reciprocal twins. The actual positions of [100] and [001] depend on the composition; the diagram shows the approximate positions for bytownite. K_1 (glide plane) and K_2 are planes of no distortion, and η_1 is the glide direction; η_2 is the line of intersection of K_2 and the plane perpendicular to K_1 containing η_1 ('plane of shear'). K_2^0 and η_1^0 refer to positions occupied before twinning; θ is the obliquity. Twin axes are indicated by rotation arrows. Albite twins have irrational η_1 and K_2, and pericline twins have irrational η_2 and K_1.

twins occasionally included in discussions of plagioclase twin laws (e.g. Deer, Howie, and Zussmann, 1963, p. 29). These are reported as having [100] as twin axis and an irrational $(0kl)$ composition plane.[1] The formation of such twins by glide would also involve shears of 1·000 in albite and 0·969 in anorthite. These improbably large shears make a mechanical origin unlikely, and since the twins are supposed to have irrational composition planes, they cannot be growth twins. Therefore, the existence of irrational-type 'estérel' twins is highly questionable.

Pabst (1955, p. 899) stated that acline twins 'must not be considered as resulting from twin gliding'. This is true of all parallel and complex twin laws in plagioclase, because they would involve distortion of the composition plane, and hence cannot be formed by simple shear parallel to this plane.

Stepped and abruptly terminated twins

Shape. In contrast to the gradual changes in direction of the composition planes of lenticular twins are the angular, steplike changes in direction shown by the second group of twins in the Broken Hill plagioclase. Both simple and lamellar twins of this type are present (fig. 7), lamellae maintaining a constant thickness between steps. Typical examples are shown in figs. 7 and 8. Where lamellar twins are present, there are only 3 to 5 (rarely 7) individuals per grain. Some triangular twins at grain corners were also observed (fig. 7g). Twin laws for stepped twins are shown in tables I and II; albite twins predominate. Where a grain is twinned on more than one law, the twins have a common composition plane (e.g. fig. 7i). Stepped twins are much less common than lenticular twins.

Attempts have been made to measure the orientation of the planar steps and of the terminations formed where a twin stops within a grain. Small steps are difficult to measure accurately, and precision is also lost during plotting operations, but about 50 relatively accurate determinations were made on steps and terminations on albite twins. In albite twins the only plane common to both individuals is (010), and all steps and terminations are irrational planes. However, the measurements indicate that many of them lie close to planes of the forms {021}, {001}, {101}, {241}, {211}, {130}, {061}, {111}, and {023}, using interfacial

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[1] The original usage of the term 'estérel' by Lacroix was as a synonym for 'ala', judging from Burri (1962, p. 195). The idea of an irrational composition plane was presented by Franke (1920) as a theoretical, geometrical discussion, without observational evidence.
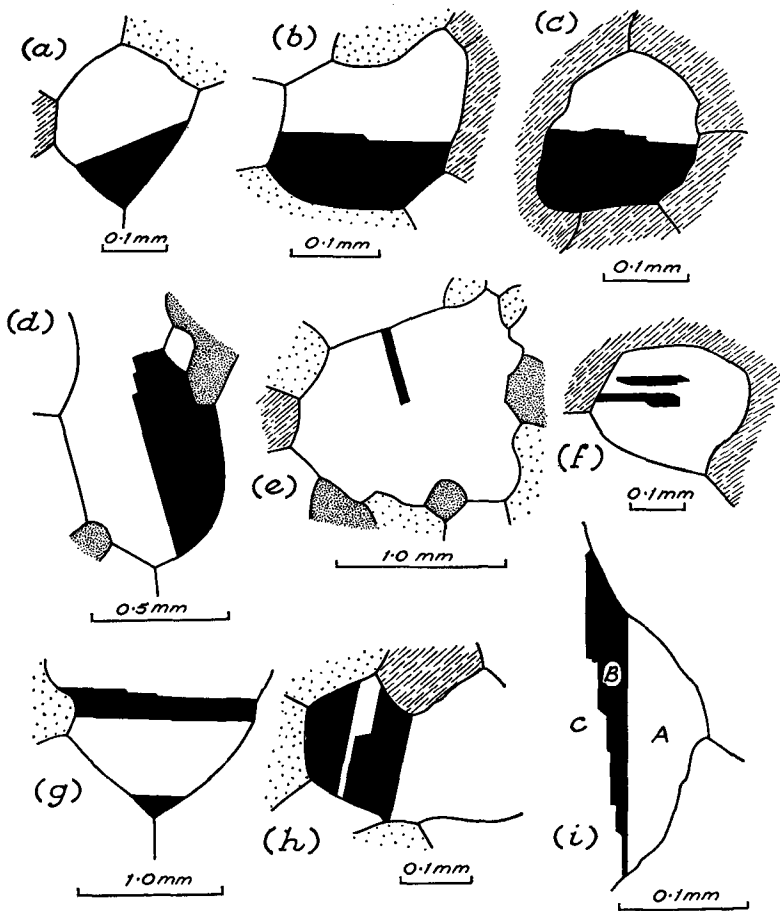
Fig. 7. Typical examples of stepped and abruptly terminated twins in plagioclase in Broken Hill mafic gneisses. Diagram D shows the intersection of an incoherent twin interface with a plagioclase grain boundary. Diagram F shows an 'included' lamella. Twin laws are: albite (A, D, E, F, G, H), Carlsbad (C), and albite-carlsbad (B); in diagram I the laws are: albite (AB), Carlsbad (BC), and albite-carlsbad (AC). Other minerals are hornblende (hachured), clinopyroxene (light stipple), and orthopyroxene (dense stipple).

angles for anorthite published by Naumann and Zirkel (1898) and Miers (1902). These are common forms in plagioclase crystals, and so are composed of low-energy faces. Perhaps the steps and terminations, though irrational, are as close as possible to equivalent low-energy
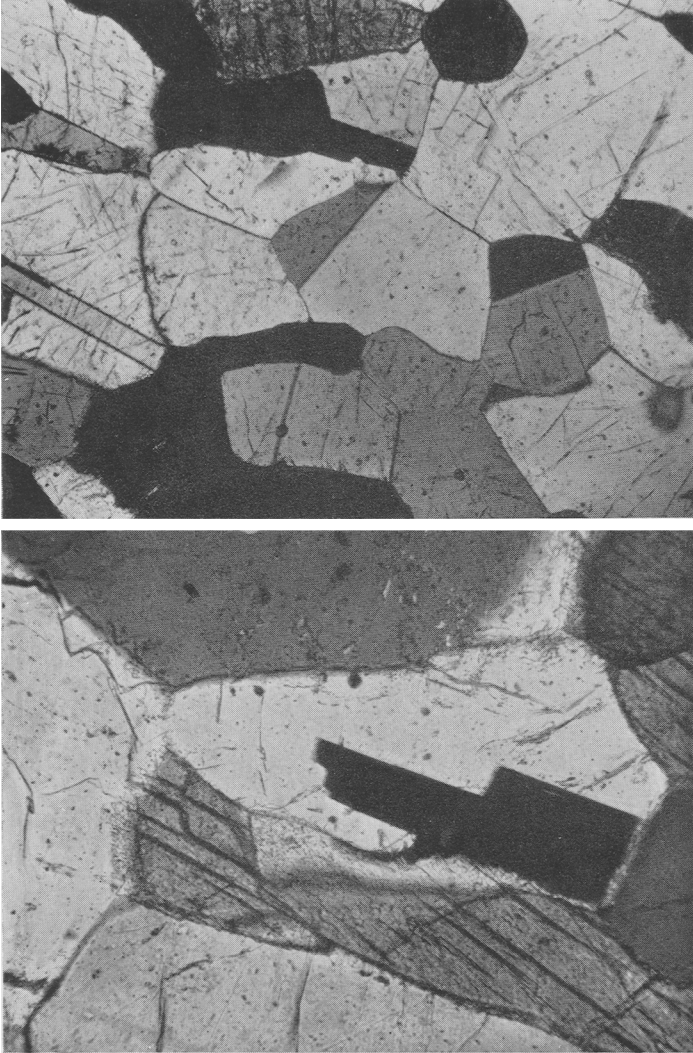
FIG. 8. A (top): Polygonal grains of plagioclase, most of which are untwinned, but some of which show growth twins. Most of the twins are simple, but a stepped lamellar twin occurs in the grain to the left. × 33. B (bottom): Stepped and abruptly terminated twin in plagioclase. × 137.

planes in both individuals. A more accurate method would be needed to prove this, however.

Origin. The shapes of these twins closely resemble those of annealing twins (solid state growth twins) in face-centred cubic metals, formed during grain growth in the solid state, as illustrated by Burke (1950), Cahn (1954), Hall (1954), and Bolling and Winegard (1958). Therefore, they may have had a similar origin, although this needs experimental verification. Buerger (1960) suggested the existence of such twins in plagioclase, calcite, and dolomite, and recommended a search for them. Vance (1961) and Seifert (1964) have listed criteria for the recognition of growth twins in plagioclase, referring only to twins that appear to have been formed during crystallization of silicate liquid. The stepped twins in the Broken Hill mafic gneisses show features identical to those in igneous plagioclase, but there tend to be fewer individuals per grain, and triangular twins occur at some grain corners, as would be expected if the twins originated by growth of grains in the solid state (see below). Isolated (enclosed) twin lamellae, such as those shown in fig. 7F, have been produced experimentally in zone-refined lead during grain growth (Bolling and Winegard, 1958, fig. 4).

The grain boundary configuration of the mafic gneisses, with its strong tendency towards smoothly curved interfaces and polygonal grain shapes (fig. 1A; fig. 8A), suggests that the grains have undergone growth and adjustment in the solid state. The process of grain growth has been discussed for metal aggregates by Harker and Parker (1945) and Smith (1948), and the mechanism has been applied to ceramic aggregates by Kingery (1960). Polygonal aggregates similar to annealed metals have been produced experimentally in periclase, fluorite, and anhydrite (Buerger and Washken, 1947), calcite (Griggs *et al.*, 1960), quartz (Carter *et al.*, 1964), and sulphide minerals (Stanton, 1964). The grain configuration has been shown by Smith (1954) to be a very general natural phenomenon, reflecting a tendency for polycellular aggregates to completely fill space and acquire a minimum total interfacial area. The ideal configuration discussed by Smith applies only to aggregates with effectively isotropic interfacial energies, and, although the tendency towards polygonal grains with 120° dihedral angles is evident in the mafic gneisses, there are many departures from the ideal configuration. This is presumably due to structural anisotropy in plagioclase and the mafic minerals present, a problem worthy of further investigation.

The process of formation of annealing twins during grain growth in

face-centred cubic metals has been described by Burke (1950) and Fullman and Fisher (1951). Stacking faults are produced at grain corners, forming planar twin interfaces, which increase their area as required by further growth of the grains concerned, but which cannot migrate in directions normal to themselves. If no other stacking fault is produced at a later stage, the result is a simple twin, but if another stacking fault re-establishes the original orientation, a lamellar twin is formed. Nucleation at grain corners leads to local preservation of triangular twins initiated just before the cessation of grain growth.

A stable stacking fault can form only where 'the free energies of the boundaries between a grain's neighbours and its twin would be less than that of the boundaries between the neighbours and the grain itself' (Fullman and Fisher, 1951, p. 1351). This can be achieved, despite the replacement of two boundaries by three, because the twin interface makes a relatively small contribution to the total free energy of the three boundaries.

Incoherent interfaces[1] may be formed, either as steps in the composition plane or as terminations to twins ending within grains, provided that continued grain growth brings about an energetic situation necessitating the dissociation of the coherent twin interface from a grain boundary (Fullman and Fisher, 1951, p. 1352). Incoherent interfaces have much higher energies than coherent interfaces (see below), so that as grain growth continues, the dissociated lamellar twin will shrink parallel to its boundaries in an attempt to remove the high-energy incoherent termination by removing the twin itself. Eventually the twin may disappear, restoring the original orientation of the grain; this process helps account for the typical broadness of annealing twins (Burke, 1950).

Twin laws. Frequencies of twin laws in stepped twins are shown in tables I and II. In rocks showing negligible amounts of mechanical twinning (table II), the prevalence of untwinned plagioclase, the relative abundance of simple albite twins, and the occurrence of some simple albite-carlsbad twins are especially noteworthy.

Turner (1951) noted the prevalence of untwinned plagioclase and simple albite twins in some metamorphic rocks of the greenschist facies.

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[1] Fullman (1951*b*) established that the incoherent interfaces in copper are irrational planes lying between a (113) plane of one orientation and a (335) plane of the other. These planes are close together but do not coincide, so that the measured, relatively high energy of the incoherent interfaces is connected with the observed irrationality. The same may well be true of incoherent interfaces in albite twins in plagioclase.

Tobi (1962) also noted abundant simple albite twins in greenschists, and added the frequent observation of simple twins on the albite-carlsbad law. Tobi noted further that lamellar twins in these rocks were abruptly terminated. These writers intimated that these features were characteristic of low-grade metamorphic rocks, although Turner noted that they may be general features of metamorphic plagioclase. Their occurrence in Broken Hill mafic gneisses of the granulite facies suggests that metamorphic grade has less of an effect than general conditions of metamorphic grain growth. Where no mechanical twins have been produced by post-crystalline deformation, the plagioclase shows only a few growth twins, with simple albite-law twins being much more prominent than in other geological environments. Apparently the low energy of the twin interface favours the formation of albite twins in preference to others, as in all environments, but the difficulty of twin nucleation in the solid state favours an increased proportion of simple growth twins in metamorphic rocks.

Seifert (1964, pp. 314, 315), in reference to Turner's description of simple (therefore, growth) twins in metamorphic rocks, found difficulty in applying to metamorphic plagioclase the concept that supersaturation and rapid growth are necessary for the formation of growth twins (Buerger, 1945). The problem is removed if the mode of formation of growth twins in metamorphic plagioclase is similar to that of annealing twins in metals. The preservation of such twins is severely limited by two main processes, namely: the mode of nucleation at grain corners, such that stacking faults are not perpetuated unless the orientation relationships between adjacent grains are favourable, which is a fortuitous circumstance in a random aggregate; and the strong tendency for the removal of twins with incoherent terminations during continued grain growth. In contrast to this behaviour, recurrent supersaturation may produce many lamellar growth twins in igneous plagioclase and, although many incoherent terminations are formed fortuitously, they are perpetuated by quenching. Thus the fundamental difference in environment accounts for the fact that, although growth twins can occur in both types, they are much more abundant in igneous than in metamorphic plagioclase.

Energies of coherent and incoherent interfaces. Buerger (1945, 1960) has emphasized the low energy of coherent twin interfaces. Smith (1948) noted that in metals the low energy of twin interfaces relative to grain boundary energies is reflected in the small degree of deflection of grain boundaries where they meet twin boundaries. The same can be

said for intersections of growth twin interfaces with grain interfaces in the Broken Hill plagioclase, except that the deviations appear to be variable, which suggests that, in contrast to cubic metals, the effect of structural anisotropy in plagioclase is relatively large. Attempts have been made to measure the ratio of albite-twin boundary energy to
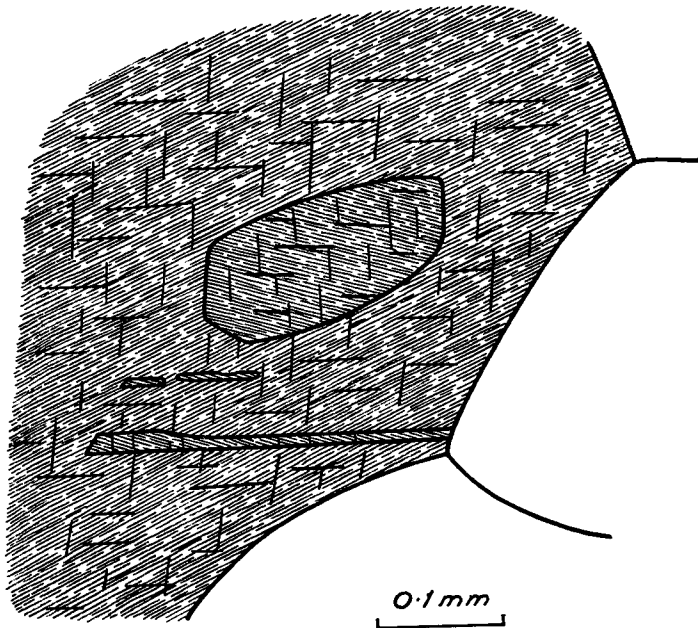

FIG. 9. Examples of small and large bleb-like twins (albite law) are shown in the centre of a plagioclase grain. The diagram also shows numerous thin antiperthitic lamellae (drawn larger than normal), which are common in the plagioclase of some of the Broken Hill mafic gneisses.

grain boundary energy, by means of dihedral angles, according to the methods of Fullman (1951*a*, 1951*b*), but preliminary results were variable, presumably because of the anisotropy mentioned above.

The energies of incoherent interfaces of annealing twins in metals have been shown to be markedly higher than those of coherent interfaces (Fullman, 1951*b*). Intersections of incoherent twin terminations with grain boundaries are rare in the Broken Hill mafic gneisses, only two examples having been found. However, the grain boundaries are distinctly 'drawn in' by the incoherent interface (fig. 7*d*), suggesting

that the incoherent interface has a relatively high energy; the configuration is almost identical to the illustration given by Fullman (1951b, p. 459, fig. 6).

The problem of 'bleb-like' twins

Rarely, isolated lamellae and twin 'patches' occur within plagioclase grains. They generally have rounded terminations and are best described as 'bleb-like' (fig. 9). They resemble annealed mechanical twins, as described by Mathewson (1928), and may be original mechanical twins that have not been completely removed during grain growth of the plagioclase.

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Addendum. After completing this article, the writer's attention was drawn to a recent paper by J. Starkey and W. L. Brown (Zeits. Krist., 1964, vol. 120, p. 388), which reports the experimental formation of mechanical twins in anorthite. Some were elastic twins, others permanent. Both albite and pericline twins were produced and photomicrographs clearly reveal the lenticular shapes of the lamellae, thus supporting the contention that lenticular twins in natural plagioclase are of deformational origin.