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THE METAMORPHIC AND STRUCTURAL SEQUENCE IN THE PRECAMBRIAN OF THE CRADLE MOUNTAIN AREA, TASMANIA

by

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Abstract

The metamorphic basement in the Cradle Mountain area consists of low-grade metasedimentary rocks, phyllite, schist, and an amphibole-bearing schist of igneous origin, that occur in steeply-dipping ENE-trending belts. The microfabric of the pelitic schists consists of a bedding foliation (S_1). This has been crenulated and almost obliterated by a schistosity (S_2), which has in turn been crumpled by a strain-slip cleavage (S_3). These surfaces are related to two mesoscopically identifiable phases of folding (F_1 and F_2).

Textural analysis of the metamorphic minerals indicates a main phase of Barrovian-type metamorphism which reached the upper greenschist facies and attained its climax pre-kinematically with respect to F_1. A second phase of metamorphism was comparatively minor and syn-kinematic with F_2. The present distribution of metamorphic grade is now controlled by the regional transposition associated with F_2. A regional zonal arrangement of phyllite up to almandine schist grade is preserved in a remnant block unaffected by F_2.

Small but significant differences in the metamorphic and structural sequence between the area and elsewhere in the metamorphic basement of Tasmania appear to illustrate the independent and probable diachronous nature of the components of the Frenchman orogeny.

Introduction

The Precambrian rocks of the Cradle Mt area occupy the NW portion of the central older metamorphic basement of Tasmania (the Tyennan nucleus). They consist of thick, sub-parallel belts of pelite and quartzite which generally dip steeply, and trend ENE parallel to the edge of the nucleus. These lithons show strong internal deformation due to multiple fold movements, and contain mineral assemblages indicative of the lower and upper greenschist facies of regional metamorphism. The regional metamorphism reflects the Frenchman metamorphic period (Spry, 1963a) which affected the whole of the Tyennan nucleus in Tasmania.

No stratigraphic section can be suggested within the basement because marker horizons are lacking and a major coherent structure is not revealed. Although the major lithological layering of pelite and quartzite probably reflects original sedimentary layering, there is much folding and transposition of surfaces, and the pelite and quartzite interfaces are the loci of tectonism. Sedimentary features such as cross bedding and graded bedding, however, are locally preserved. The original sedimentary pile was probably a thick sequence of siltstone and orthoquartzite.

The rocks of the Cradle Mt area are equivalent to similar schists and quartzite in the adjacent Middlesex Quadrangle. Such rocks have been termed the Dove Group and the Fisher Group (Spry, 1958; Jennings, 1963). The Dove Schist is equivalent to the dominantly pelitic rocks of the northern portion of the Precambrian basement at Cradle Mt, and the Fisher Group, to the southern dominantly quartzite portion.

The Tyennan nucleus is flanked to the N and W by thick sequences of eugeosynclinal Cambrian rocks. Sedimentary rocks of a problematical age occur along the edge of the nucleus between the Precambrian and a thick sequence of Cambrian porphyry. These are not incorporated into the Tyennan nucleus, and their structural relations are not discussed here.

Remnants of the flat-lying Permian succession cover portions of the Precambrian basement in the Barn Bluff and Mt Inglis area (Gee and Burns, 1968). The Permian succession was intruded by a sheet of Jurassic dolerite which now caps the higher peaks. Extensive erosion of these rocks has exhumed the pre-Permian surface which now exists as a well-formed plateau at the 1,220 m (4,000 ft) level. The Pleistocene glaciation has deeply dissected this plateau and also left extensive moraine and fluvioglacial deposits. The superficial deposits of the area have been described by Benson (1917), Jennings (1959) and Derbyshire (1968).

Petrology

Low Grade Metasedimentary Rocks

Scattered slices of indurated banded siltstone occur within the semi-pelitic belt between Lake Rodway and Granite Tor. These are generally black and grey banded, slightly glossy rocks which split preferentially along the lamination. The lighter laminae consists of angular quartz grains of medium silt grade, small detrital flakes of muscovite and chlorite, and a fine sericitic matrix which shows little recrystallisation. The darker laminae consist of very fine quartz and sericite in dirty brown, stringy bundles which have an aggregate polarisation parallel to the bedding. Probable graded bedding is present in the thinly banded phyllite and quartzite. This is expressed by an increase in the frequency of the dark sericitic bundles toward the dark layer, or by oblique slaty cleavage curving toward parallelism with the darker laminae.

Phyllite

Phyllite is common within the pelite layers and is the dominant rock in the western portion of the major pelitic belt to the N (fig. 1). This belt grades eastward into medium-grained schist and then into coarser-grained garnet schist at Waldheim.

The phyllite is well foliated and of a glossy steel-grey colour. Mesoscopic lithological banding is visible only in large outcrops. The foliation is either planar or finely anastomosing and commonly displays a crenulation lineation. A fine mineralogical segregation parallel to the foliation is visible in hand specimen.

In thin section the phyllite (*e.g.*, 63-80, 63-81, 63-82, 63-87, 63-89 from the Crisis Creek area) consists of thin lenticles, up to 1 mm thick, alternately rich in quartz and muscovite. The quartz (0.1 mm in diameter) forms a fine-grained interlocking mosaic, and the muscovite is dirty and stringy and has a strong preferred orientation parallel to the segregation. Micro-porphyroblastic albite and tourmaline occur in the micaceous layers. Specimen 63-19 from Anio Creek

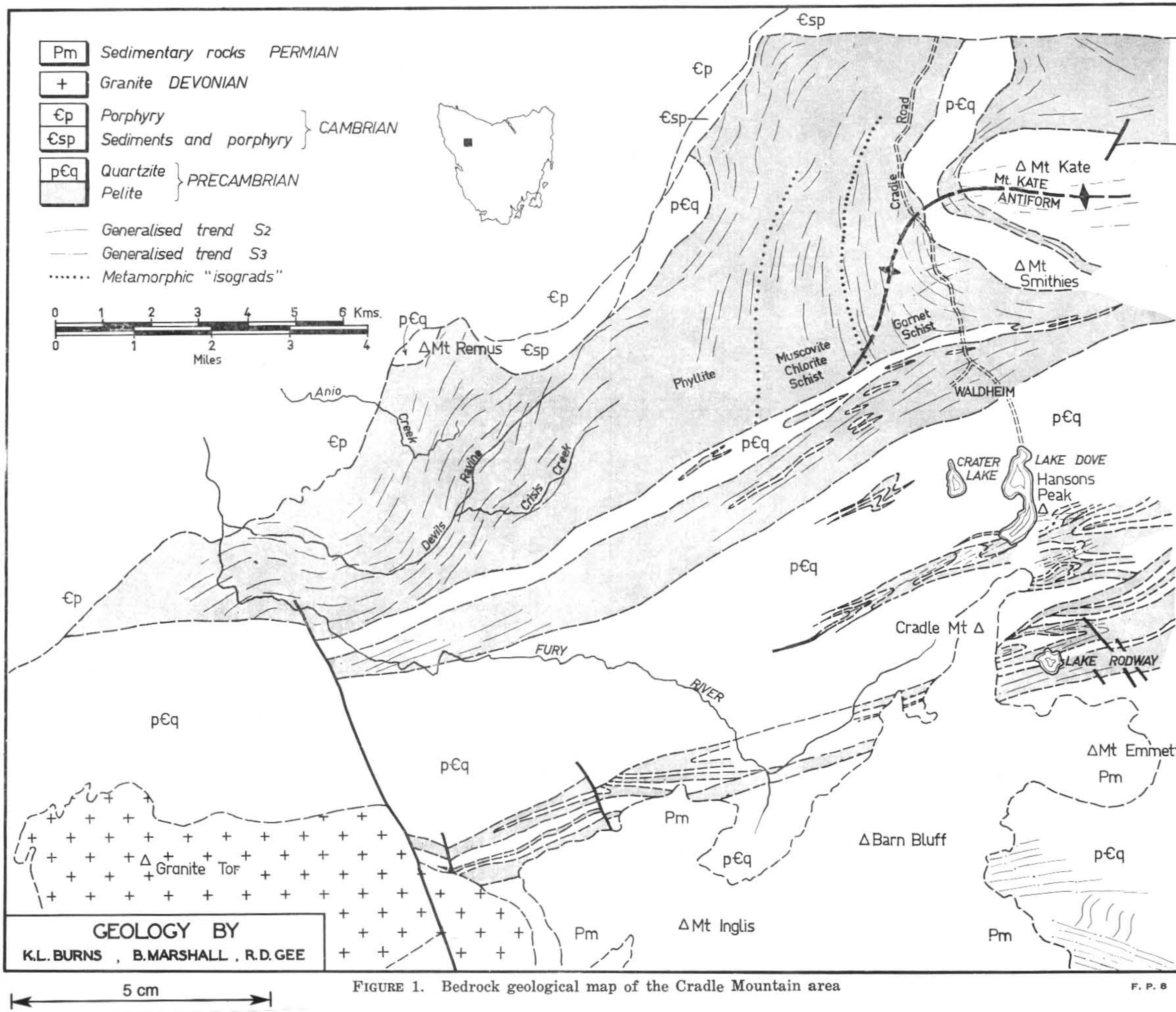

FIGURE 1. Bedrock geological map of the Cradle Mountain area

contains albite grains, 0.08 mm in diameter, generally surrounded by a fringe of minute xenocrystalline, clear chlorite (penninite?). The albite micro-porphyroblasts contain sigmoidal trails of fine, black, dusty inclusions which are continuous with the enclosing foliation. Specimen 63-81 is a coarser phyllite containing albite up to 0.2 mm, and micro-porphyroblasts of cross-fibre chlorite (anomalous blue interference colours) in flakes up to 0.3 mm.

Schist

The pelitic rocks are mostly medium-grained quartz-muscovite schists, commonly with albite and less commonly with biotite. Coarser grained garnet schist occurs along the Cradle Mt Road, N of Waldheim (fig. 1). The schists are glossy grey to brown in colour, and possess a strong schistosity due to a metamorphic segregation up to 5 mm in thickness. A lithological banding 3-30 cm thick is commonly parallel or slightly oblique to the schistosity. This banding may represent original sedimentary layering.

Quartz generally occurs in xenoblastic grains up to 0.2 mm in diameter, having a weak dimensional orientation in the foliation. These form an interlocking mosaic which encloses scattered small individual flakes of muscovite. Some textural variations occur. Specimen 64-257 contains elongate quartz grains with straight parallel borders terminated against mica flakes. Specimen 64-247A has a fine-grained quartz mosaic with common triple intersections giving pseudo-hexagonal shapes. This is probably an annealed cataclastic texture.

Muscovite is the dominant micaceous material, forming bundles along the foliation. Such muscovite flakes generally tend to be ragged and dirty, due to abundant fine inclusions of ilmenite and leucoxene and are probably the phengite variety. Muscovite also occurs as clean sub-idioblastic flakes discordant to the main foliation. Another textural type occurs as small (0.8 mm in length) clean discrete flakes, defining remnants of a micro-folded surface, within the quartz-rich layers.

Chlorite occurs as sub-idioblastic flakes up to 0.3 mm, growing either across or along the main foliation. Chlorite also occurs as prismatic stacks aligned across the foliation with a porphyroblastic habit, and wrapped by the foliation.

Biotite, distinguished from stilpnomelane by X-ray diffraction, is a common but minor constituent in most schists. It is the dominant micaceous mineral in some schists from N of Mt Inglis (63-104) and Lake Rodway (63-34) where it occurs in small (< 0.05 mm) ragged flakes commonly interleaved with muscovite in the mica-rich layers and defines the main schistosity. In the quartz-rich layers muscovite occurs to the exclusion of biotite.

Albite occurs as lozenge-shaped porphyroblasts within the mica-rich layers of the pelite. Inclusions within the porphyroblasts define an internal fabric (S_i) which can be planar, sigmoidal or strongly plicated in habit. The relationships of S_i and the schistosity are discussed later. Two types of inclusions are present: a fine, dusty black type of graphitic material, iron oxides, and possibly rutile, probably inherited from the muscovite during its replacement by albite; and a crystalline type of minute quartz, muscovite and, less frequently, tourmaline, zircon and epidote. Porphyroblasts with the dusty type of inclusions are rimmed by an opaque, earthy material. This is probably the residue from muscovite that could not be accommodated within the lattice of the growing albite. The crystalline type of inclusion is more common in the garnet schists near Waldheim.

Some of the plagioclase (n < balsam) is twinned (65-34) and this has been examined by the method of Slemmons (1962). The twinning is of a simple type with a sharp composition plane separating the two sub-units.

Consistent results from 10 determinations gave $Z \wedge \perp CP = 16° \pm 1°$, showing that the composition plane is always (010). Using the 'rough guide' of Slemmons (1962, plate 1), these values indicate a composition of An_0-An_2. In three of the determinations a reasonable twin axis lying in the composition plane was obtained indicating that the twin is not normal. In these three cases, a transverse cleavage was inclined at about 88° to the composition plane. The angle between the twin axis and the pole to the cleavage was 25°. This indicates a Carlsbad twin and using Slemmon's Plate 5, permits confirmation of the plagioclase as nearly the pure end-member. In the other seven cases, a satisfactory twin axis could not be obtained because in the stereographic projections X_1 and X_2 are never more than 4° apart and Y_1, Y_2, X_1, X_2, all fall close to the one great circle. However, by using the procedure of Emmons (1943, pp. 104-109) it can be shown that these seven cases are also not of the normal type, and are most probably Carlsbad twins.

Garnet forms porphyroblastic dodecahedra varying in size from 0.05 mm up to 2.0 mm (64-254, 64-247, 64-29), which are wrapped around by the main foliation. The crystals generally contain a few randomly distributed quartz inclusions and are sometimes cracked and altered to chlorite. Some have a zonal arrangement in which a cloudy rim, often deeply altered to chlorite (64-254), contains abundant weakly orientated inclusions of quartz. This rim is generally more fractured than the clear core, and shows a tendency to be drawn out along the foliation (64-256). Fine muscovite and quartz has grown between the core and the rim, especially in the 'eyes' of the garnet. The relations between metamorphism and the micro-structures are discussed in a later section.

A chemical analysis of garnet separated from the coarse-grained garnet schist (64-254) from near Waldheim is shown in Analysis 8 (Table 1). This material includes mainly idioblastic cores contaminated with earthy chloritic alteration material. The analysis does not balance structurally due to an excess of ferric iron. Using the divalent ions, on the basis of 24 [0] a garnet containing 66% almandine, 14% spessartite and 20% grossular is indicated. These values are approximate but indicate a dominant almandine component.

SEMI-PELITE

Semi-pelite, or thinly interbedded phyllite, schist and quartzite, is the dominant rock type in the major pelitic belt at Lake Rodway. These rocks are petrologically similar to the phyllite and schists described previously. The semi-pelite consists of quartzite bands (3-15 cm thick) with regular alternation of either fine-grained, dark bluish grey phyllite or quartz-muscovite-albite schist of a similar thickness.

QUARTZITE

Two main types of quartzite can be distinguished, a well-bedded, platy quartzite, and a schistose quartzite. The platy quartzite occurs predominantly within the two major quartzite belts in the southern half of the area, as well as in the core of the antiform on Mt Kate, and on Mt Remus. The schistose quartzite is more common in the thinner quartzite slabs within the major pelitic belt in the northern half of the area. This broad spatial distribution reflects partly the influence of argillaceous impurities, and partly the more intense folding and transposition associated with the pelitic belts. However, even the most massive quartzite has a microscopic foliation.

The least schistose quartzite occurs on Mt Remus at a shallow structural level. The quartzite occurs in planar slabs from 5-100 cm thick, devoid of internal lamination. The units are defined by a plane of parting and not a penetrative schistosity, giving the appearance of a well-bedded orthoquartzite. A weak foliation parallel to the bedding(?) is defined (*e.g.* 63-79) by a planar orientation of small (0.3 mm) dispersed, clean, muscovite flakes. Ninety-eight per cent of the rock consists of quartz grains (0.03-0.1 mm) which form an interlocking mosaic. In places the quartz grains have a near-hexagonal shape and triple-point intersections are common, suggesting post-kinematic or static recrystallisation.

The typical platy quartzite varies from thinly bedded to thickly bedded. The slabby nature is defined by discrete planes of parting which in some cases are due to thin layers of schistose micaceous quartzite or pelitic material. Within the slabs is a weak colour-banding which is more apparent on weathered surfaces. This internal lamination is due to grain size differences, shreds of chlorite (64-217B), and trails of small hematite grains (64-249A). The lamination is mostly planar, but on Hansons Peak it forms a series of nested festoons within the planar slabs, commonly showing tangential and truncated contracts. This internal lamination is almost certainly the original sedimentary lamination and cross lamination.

Despite the bedded appearance of the quartzite, a microscopic foliation is always visible, due to a preferred dimensional orientation of quartz and mica. In the more micaceous and schistose quartzite (*e.g.* 64-255), the foliation is expressed by stringy bundles of mica flakes, separated by one or two layers of tabulate quartz grains.

In general, the schistose quartzite is pure, and was also originally an orthoquartzite. In thin section it consists dominantly of an interlocking mosaic of xenoblastic, undulose quartz grains (0.1-0.4 mm). Muscovite and chlorite occur as clean sub-idioblastic flakes and form up to five per cent of the rock. The chlorite is pale green and weakly pleochroic, with an extinction of 8° and weak, but not anomalous, birefringence. It has the properties of clinochlore, and appears to be a primary metamorphic mineral.

Secondary chlorite occurs in some quartzites (*e.g.* 64-258, 64-259 from Mt Kate). This mineral occurs as fine, ragged flakes or more commonly as alteration rims around the muscovite and primary chlorite, and penetrating along the basal cleavage.

Garnet occurs in the schistose micaceous quartzite. It exhibits well developed sieve-structures (fig. 3b) with up to 70 per cent of square- or rectangular-shaped quartz grains, defining an internal surface (S_i) at an angle to the external foliation of the rock. Although the external foliation, defined by the preferred orientation of mica and of elongate quartz, is slightly deflected around the garnet; it is basically continuous with S_i.

Minor amounts of feldspar (albite?) occur in the less-pure quartzite, as scattered xenoblastic grains interlocked in the quartz mosaic. This is texturally distinct from the albite in the pelitic rocks which occurs as porphyroblasts confined to the micaceous layers. The xenoblastic type of feldspar was probably of detrital origin.

Green tormaline is a common accessory in the quartzite (64-252, 64-225) and occurs as idiomorphic prisms with their long axes lying along the foliation. The tourmaline is generally fractured and wrapped around by the foliation.

Other accessory minerals in the quartzite include opaque oxides and zircon; they are probably of detrital origin.

Amphibole Schist

Amphibole schist crops out at the 1,220 m (4,000 ft) level in the SW corner of the wall of Crater Lake. It occurs as slabs concordant with the main lithological layering.

The rock is a dense, dark green to black, well foliated and knotted schist with feldspar up to 2 mm in diameter. It (64-30) consists of albite porphyroblasts (up to 40 per cent of the rock) in a foliated matrix of green actinolite (0.15 mm in length), and biotite. Granular (0.05 mm) epidote forms trails along the foliation, and small amounts of calcite, quartz and pyrite are present.

Abundant inclusions of clinozoisite(?), epidote and actinolite are arranged within the albite in sigmoidal trails (S_i) of varying degrees of curvature. In many porphyrobasts S_i is perfectly continuous with the external foliation (S_e) and the actinolite needles penetrate the albite. However, there are microscopic zones of later deformation, in which the early foliation is crumpled, and S_i and S_e are discordant. In these domains biotite and chlorite have recrystallised in random orientation, and the albite porphyroblasts are fractured and penetrated by thin veinlets of calcite.

A chemical analysis of the rock is given in Table 1, Analysis 3. This analysis gives a CIPW normative composition of orthoclase 10%, plagioclase (An_{35}) 43%, clinopyroxene ($CaO_{0.50}$, $FeO_{0.13}$, $MgO_{0.37}$) 10%, orthopyroxene ($En_{0.74}$, $Fs_{0.26}$) 16.5%, olivine ($Fa_{0.3}$, $Fo_{0.7}$) 10.3%, magnetite 4%, ilmenite 1.5%, calcite 0.5%. This suggests that the rock is an albitised olivine dolerite.

Textural Sequence

Particularly in pelitic rocks, microfabric analysis of such features as grain shape, the relationships of grains to s-surfaces and lineations, and the relationships of the various s-surfaces provide a record of the metamorphic and structural development of the fabric. Criteria for chronological analysis have been outlined by Spry (1963b) and Zwart (1963).

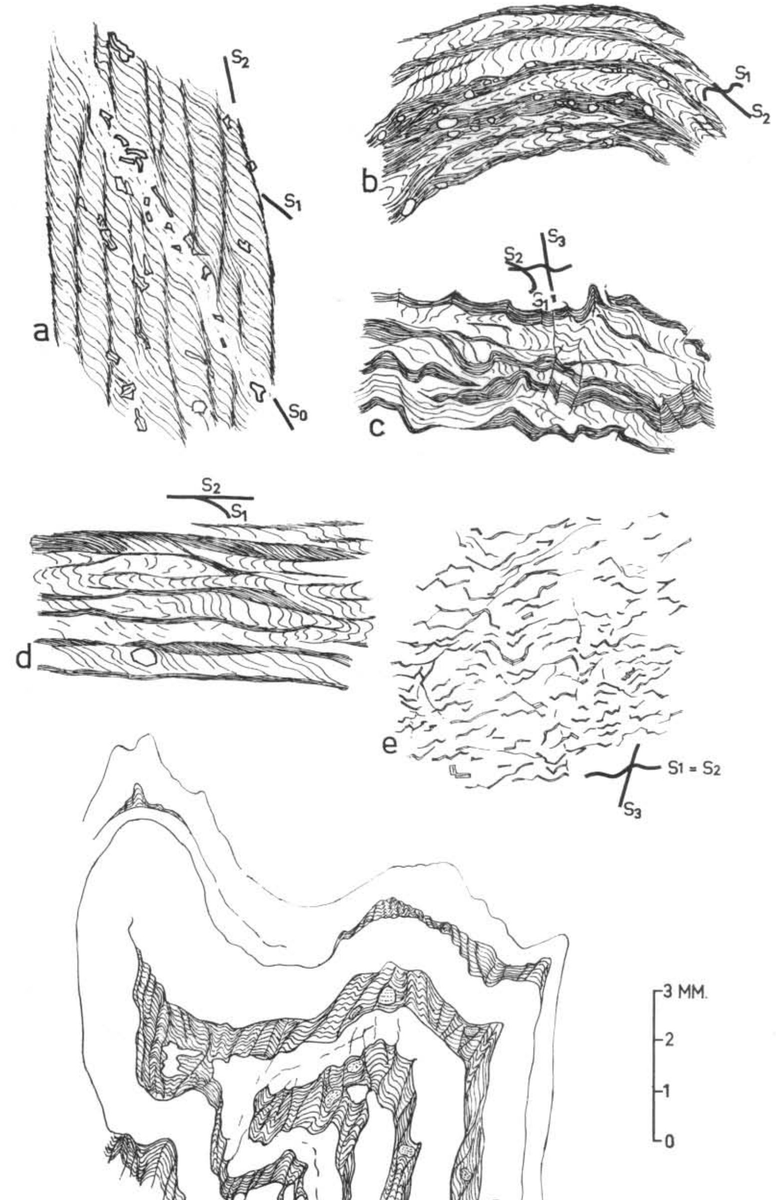

FIGURE 2. Microscopic relations of individual foliations

5 cm

Surfaces in the Pelitic Rocks

The basic pattern in the pelitic rocks of the Cradle Mt area is one in which an older microscopically visible foliation has been crenulated and almost obliterated by a main schistosity which in turn, has been crumpled, but not obiterated, by a later cleavage. There is no evidence that this sequence has been repeated, such that the main foliation in one area is transposed in another area by a later dominant foliation. Thus, in order to determine the textural sequence, all processes have been related to the main schistosity, as a specific 'time' horizon.

S_1 bedding foliation

The oldest surface (S_1), which is found in both the phyllite and schist, occurs as curved or sigmoidal trails of small single muscovite flakes between the mica foliae of the main schistosity (S_2). Where S_2 is not so fully developed S_1 is well preserved (fig. 2a) and is expressed as a preferred orientation of fine muscovite and dimensional orientation of small lenticular quartz grains. Mesoscopically, S_1 parallels a colour and compositional banding up to 10 mm in thickness. In the pockets of lower grade metamorphism this banding is expressed as fine-grained and coarse-grained laminae in which original siltstone textures are recognisable. The S_1 surface was possibly a glossy bedding fissility in rocks that were probably argillites before the onset of the S_2 movement.

Even in the coarse-grained schists S_1 is still preserved, and can be correlated in thin section and hand specimen with the lithological and colour banding. The S_1 surface in these schists appears to have been a slightly segregated phyllitic foliation, parallel to the bedding.

S_2 schistosity

The S_2 surface is a crenulation foliation derived by mechanical rotation of pre-existing S_1 micaceous minerals into a new position. Figure 2a shows an early stage in the transposition of S_1. In its final development it is expressed as an alternation of muscovite-rich and quartz-rich folia with remnants of S_1 in the quartz-rich folia (fig. 2b, 2c). The micro-crenulation appears to have taken place by a process of bend-gliding on the S_1 micas, rotating them into a near-axial plane position on the limbs. The crenulations are persistent along their axial surface, and there has been noticeable extension of the mica books in the crests, allowing the syn-kinematic migration of quartz from the limbs to the crest. This process seems to account for the compositional segregation parallel to S_2 in the schist and phyllite. In the schists S_2 is accentuated by syn-kinematic and post-kinematic recrystallisation of muscovite (fig. 2d).

S_3 strain-slip cleavage

This surface is present only in certain structural belts characterised by mesoscopic refolding. It has the characteristics of a strain-slip cleavage and may be seen as a finely-spaced discrete planar parting that cuts across S_2 at a high angle. It is readily distinguished from S_2 by its style and the paucity of related recrystallisation, even when deformation has been strong.

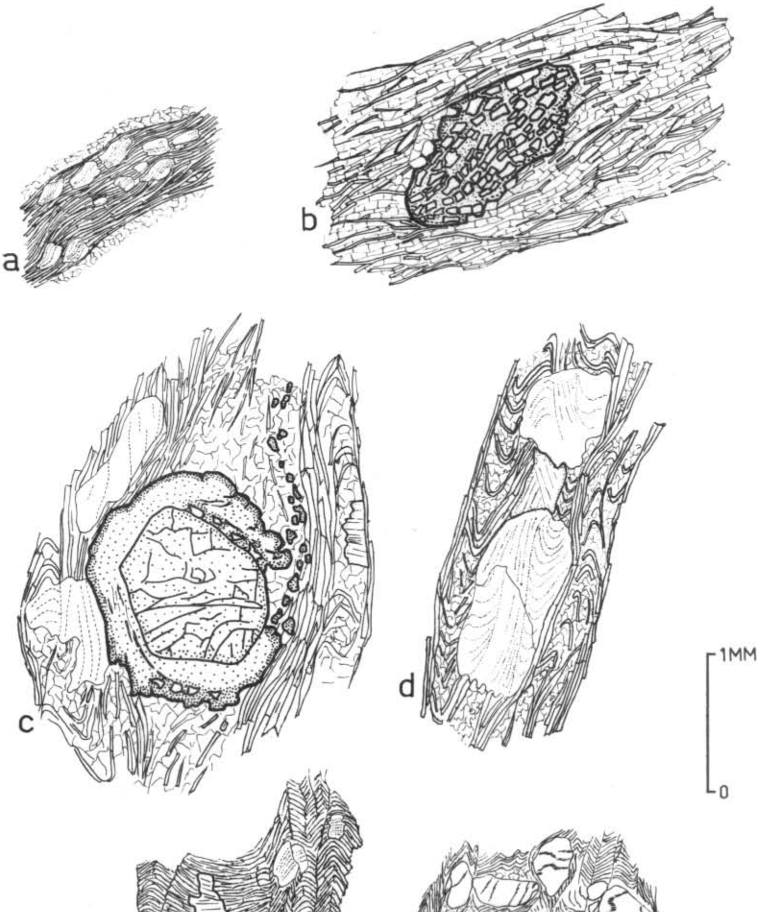

FIGURE 3. Microscopic relations of minerals

5 cm

In the phyllite, S_3 is defined by the axial planes of angular crenulations of S_2, 0.2-1.0 mm apart. Small displacements commonly occur and the cleavage planes are accentuated by stringers of black opaque graphitic material, and brown iron staining. There has been no rotation of earlier mica into the new cleavage and no growth of new muscovite in the new cleavage.

In the coarser grained schists S_3 is a more widely spaced (1-3 mm) chevron folding (fig. 2c). The muscovite books have commonly split and quartz has recrystallised in the openings.

Surfaces in the Quartzites

The correlation of the various surfaces in the pelites and quartzites can be made in field exposures. The platy parting, which is the most conspicuous surface in the quartzite, is parallel to the faint internal colour lamination and is considered to be a bedding foliation analogous to S_1 in the pelite.

In thin section there is a conspicuous foliation expressed by a dimensional orientation of muscovite, chlorite and in some places tabulate quartz. It is parallel to S_1 on the limbs of isoclinal folds, but is oblique to S_1 in the crests and holds an axial-plane relationship. On the mesoscopic scale this foliation occurs as a faint 'grain' on glassy surfaces, or as feathery indentations of more schistose material in the cores of folds. It is analogous to the main schistosity S_2 in the schists which is also oblique to the lithological layering.

In the quartzite at Hansons Peak, Mt Kate and Lake Rodway, S_2 is cut by a surface parallel to, and continuous with, the S_3 strain-slip cleavage of the pelite. This surface is a flaggy parting spaced from 6 mm to 2 cm apart and is parallel to the axial planes of the later folds. In a mullion zone on Hansons Peak the strong mica foliation is crumpled by a series of angular micro-chevron folds with planes spaced at 2-10 per mm (fig. 2e). These structures bend and split the mica flakes without post-cleavage recrystallisation of muscovite. The actual cleavage planes are not visible in the quartz mosaic, but in places the cleavage appears as trails of a very fine cryptocrystalline mosaic which may result from incipient mortar texture.

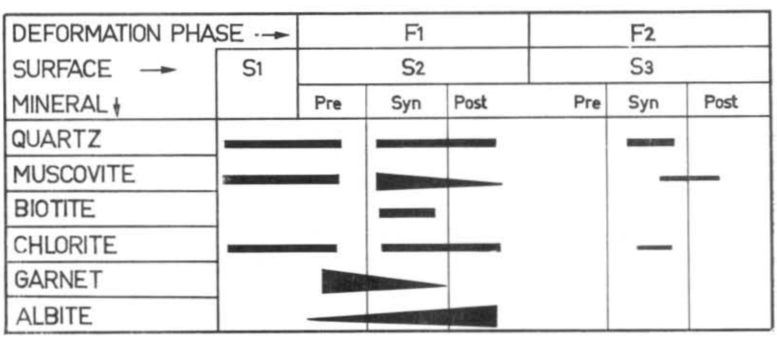

Figure 4. Relation between tectonic surfaces and metamorphic crystallisation in the pelitic rocks

Crystalloblastic Sequence

The petrographic features allow mineral species to be divided into textural types that define different growth periods. These are summarised in Figure 4.

Muscovite

(*a*) The earliest metamorphic muscovite occurs in the phyllite as small flakes with a preferred orientation lying parallel to the S_1 bedding foliation.

(*b*) Stringy aggregates of dusty flakes that define S_2, formed syn-kinematically with respect to the S_2 movements.

(*c*) Clean sub-idioblastic flakes orientated parallel to, or across S_2, are post-kinematic to S_2 and in part mimetic.

(*d*) Clean sub-idioblastic flakes which grow across both S_2 and S_3, and are not deformed by S_3, are post-kinematic with respect to S_3 deformation.

Quartz

(*a*) The earliest recognisable metamorphic quartz occurs as elongated grains closely interlayered with muscovite: this defines S_1.

(*b*) Quartz, generally elongate within the quartz-rich layers of S_2, is syn-kinematic with respect to S_2.

(*c*) Interlocking quartz mosaics in the vicinity of S_3 are presumably syn-kinematic in relation to S_3.

Garnet

(*a*) Idioblastic, inclusion-free garnet around which S_2 is deflected, is probably a non-kinematic garnet, predating the formation of S_2.

(*b*) Many examples of the previous type of garnet have xenoblastic rims with inclusions. Such garnet is commonly a locus of S_2 deflection and may be strewn out in S_2 (fig. 3c). In some idioblastic rims the inclusions of quartz have a tendency to be arranged in curved trails. This suggests that the latter part of growth was syn-kinematic with respect to S_2.

(*c*) Garnet with sieve structures in the quartzite (fig. 3b) has several features indicating growth pre-kinematic or early syn-kinematic to S_2. These include the obvious rotation, continuity of S_e and S_i, dominantly straight or only slightly sigmoidal S_i, and the rectangular inclusions showing less flattening than the quartz outside the garnet. This may be an example of post-crystalline flattening causing rotation of the foliation rather than of the garnet (Ramsay, 1962).

Albite

(*a*) Uncommon examples of albite (63-104, from the pelite band north of Mt Inglis) have a straight or slightly curved S_i truncated by, but deflecting S_2. The albite is thus pre-kinematic with reference to S_2.

(*b*) Albite, which partially deflects S_2, but which has a slightly sigmoidal S_i continuous with S_2 (fig. 3a), is syn-kinematic to S_2.

(*c*) Most of the albite porphyroblasts in the schist and phyllite contain helicitic trails continuous with S_2 and commonly contain the included remnants of S_1 transposed to S_2 (fig. 3c, 3d). The albite occurs in the muscovite foliae, and does not disturb the S_2 schistosity. In both phyllite and schist the S_3 cleavage is later than albite (fig. 3e, 3f). These features indicate a replacement growth, post-kinematic to S_2, and pre-kinematic to S_3.

Chlorite

(*a*) Some phyllite contains sub-idioblastic flakes of chlorite with a porphyroblastic and cross-foliate habit that deflects the S_2 muscovite. Chlorite of a similar age also occurs parallel to S_1 and crenulated by S_2 (fig. 2a). Such chlorite is pre-kinematic to S_2.

(*b*) In the coarse-grained schist, sub-idioblastic chlorite flakes are interleaved with, and grow across, S_2 muscovite. This is partly mimetic and is post-kinematic to S_2. Similar megacrysts, growing across S_2, and cut by S_3, occur in the phyllite (fig. 3e).

(*c*) Many of the quartzites contain sub-idioblastic flakes with a strong preferred orientation and are interleaved with tabular quartz and muscovite (fig. 3b). This chlorite is syn-kinematic to S_2.

(*d*) Late chlorite, as an alteration product of garnet and primary chlorite, is probably related to the S_3 movements.

TABLE 1

CHEMICAL ANALYSES OF PRECAMBRIAN SCHISTS FROM THE CRADLE MOUNTAIN AREA

	1	2	3	4	5	6	7	8
SiO_2	66.6	66.1	50.8	68.3	63.3	76.2	76.0	32.8
Al_2O_3	13.7	17.5	12.7	13.5	18.9	11.5	14.1	19.2
Fe_2O_3	1.1	1.7	2.9	4.3	1.5	1.4	0.68	11.6
FeO	5.5	3.9	7.0	2.6	4.9	2.1	0.74	24.4
MnO	0.22	0.34	0.16	Tr	0.14	Tr	Tr	4.9
TiO_2	0.49	0.35	0.85	0.37	0.51	0.20	0.50	0.35
P_2O_5	0.08	0.10	0.09	0.10	0.08	Tr	Tr	Tr
CaO	1.5	0.19	5.9	0.21	0.21	–	–	3.0
MgO	3.6	1.6	10.6	3.0	1.6	1.4	0.71	1.1
Na_2O	2.0	0.69	3.3	1.2	0.83	2.3	1.1	0.10
K_2O	3.5	3.4	1.7	3.3	4.1	2.4	4.3	0.38
$+H_2O$ ..	1.9	3.6	3.1	3.2	3.7	1.9	2.1	2.0
$-H_2O$ ..	0.12	0.23	0.26	0.31	0.21	0.29	0.20	Tr
CO_2	–	–	0.23	–	–	–	–	Tr

Tr=Trace

1. Biotite-albite schist, plateau N of Mt Inglis (63-104).
2. Quartz-muscovite-albite-garnet-chlorite schist, Mt Smithies (64-29).
3. Amphibole schist (igneous), SW wall of Crater Lake (64-30).
4. Quartz-chlorite-biotite-albite schist, Lake Rodway (63-105).
5. Quartz-muscovite-albite-garnet-chlorite schist, Cradle Mt road, 1 km N of Waldheim (64-254).
6. Quartz-albite-chlorite schist, Twisted Lakes (69-13).
7. Low-grade quartz-muscovite-chlorite metasediment, Artists Pool, 1.5 km S of Lake Dove (69-16).
8. Garnet separated from 64-254 (Analysis 5).

Biotite

Biotite occurs interleaved with muscovite defining S_2 (63-104), and is crenulated by S_3 (69-16). It is thus syn-kinematically related to S_2.

Metamorphism

Chemical analyses of selected schists are listed in Table 1. These are plotted on ACF, AKF and Thompson's AMF diagrams in Figure 5. No special corrections have been made, except that in the AMF plots, all Na_2O has been assigned to albite which occurs in all schists: this reduces the values of Al_2O_3. Analysis 7 (specimen 69-16) is uncorrected for Na_2O as it is a low grade metasediment containing no crystalloblastic albite or other metamorphic minerals. In the absence of specific mineral analyses, muscovite and biotite are shown as ideal. The chlorite band in the AMF diagram is taken from Winkler (1967, p. 61) together with FeO/MgO ratios as indicated in the whole rock analyses of garnet-free and biotite-free schists. The chlorites have MgO/FeO + MgO values ranging from 0.5 to 0.8.

The facies diagrams indicate the following metamorphic assemblages consistent with petrographic observation: chlorite-muscovite, chlorite-muscovite-biotite, and almandine-chlorite-muscovite, all with albite (An_0) and quartz. The amphibole schist occurs in the epidote-tremolite-biotite field, and also contains albite and calcite. Pyrophyllite is not observed and would not be expected from the AKF diagram. Stilpnomelane is not detected, and the schists do not have the required composition. The above assemblages indicate a middle greenschist facies of regional metamorphism, which with the incoming of almandine garnet was transitional to the upper greenschist facies. This represents a small part of what is commonly called the Barrovian metamorphic series.

The present distribution of pockets of differential metamorphism are more related to post-metamorphic deformation than to the metamorphic series. The highest grade, indicated by the garnet schist, occurs in the core of the Mt Kate antiform (fig. 1). Further W, in the crest of the antiform, the schist grades into muscovite-chlorite schist and then to chlorite phyllite. The Mt Kate antiform plunges about 30° in a general SW direction and this zonation appears to be correlated with depth.

Garnet does not occur in the schists S of a major dislocation that marks the southern edge of the Mt Kate antiform. These schists contain biotite, muscovite and chlorite and in many places are strongly transposed by the late S_3 strain-slip cleavage. In the area between Lake Dove and Lake Rodway, and on the plateau N of Mt Inglis, biotite-muscovite-chlorite schists occur in immediate juxtaposition to chlorite schists and low grade metasediments with no metamorphic recrystallisation. These areas are also characterised by the S_3 cleavage.

Structure

Polyphase folding is recognisable on the mesoscopic scale, and can be related to the textural sequence. The early phase of folding, characterised by the S_2 schistosity is common throughout the area, but the later structures are restricted to certain belts. Thus it is not possible to correlate or differentiate accurately all of the post S_2

structures, and it is possible that they represent genetically unrelated phases of deformation. A detailed orientation analysis, which is not attempted here, may reveal criteria for differentiating the post S_2 structures. For the purpose of this paper all the later penetrative surfaces are termed S_3, and are assigned to the F_2 fold sequence.

F_1 FOLD SEQUENCE

Mesoscopic folds of the F_1 sequence occur abundantly throughout the area, especially in the quartzite. They are difficult to detect in the pelite, but are commonly revealed by thin layers of quartzite forming detached fold cores. The mesoscopic folds vary in half-wavelengths from 1 mm-200 m. They vary in style from open and rounded, to highly-flattened flexural-slip folds. The folds are commonly bounded on one limb by a thrust plane which is parallel to the axial plane schistosity. The axial-plane schistosity (S_2) is generally visible only in the fold cores, although it is fully penetrative in thin section. The S_2 schistosity is commonly accentuated by the penetration of schistose leaves of pelitic material in the core of folds.

A lineation resulting from the intersection of S_1 and S_2 parallels the hinge line, but is usually seen only in the hinge areas, giving way to a lineation of different style and orientation on the limbs of the folds. This is a strong quartz fibre lineation and is generally oblique to the F_1 hinge line; parallelism is rare and is considered to be fortuitous. It is not parallel to any known mesoscopic set of folds, and appears to be a regionally pervasive fabric element in the quartzite. The significance of this lineation, whether older or younger than the F_1 folds, and its regional orientation need to be resolved.

Recumbent or reclined mesoscopic F_1 folds occur in the crest in the Mt Kate antiform. Elsewhere axial planes are essentially coplanar with the ENE trend of the steeply dipping basement slabs. The plunge of the hinges varies tremendously within the axial planes of the folds. The departure in plunge of hinges in closely adjacent folds is up to 60°. This variability of plunge is found in areas where there is no regularity that may be attributed to a second set of folds, whether earlier or later. This inhomogeneity of plunge may be an inherent feature of the F_1 folding due to differential flattening (Ramsay, 1962) of doubly plunging tight domes and basins of concentric fold form. Variability could become extreme where individual fold cores become detached and rotate independently.

F_2 FOLD SEQUENCE

The F_2 fold sequence involves those penetrative structures that deform the S_2 schistosity (along with the S_1 bedding foliation) and produce the S_3 strain-slip cleavage. The angular kinks (described later) and many of the late folds along the Cambrian-Precambrian border are specifically excluded from this classification. The F_2 structures vary in intensity and occur only in certain zones, for example, at Lake Rodway, Hansons Peak and at Mt Kate.

F_2 folding is most intensely developed 3.5 km S of Mt Emmett (fig. 1), where an E-W trending belt of gently undulating and shallowly plunging quartzite, containing a few recumbent mesoscopic (F_1) folds, is truncated to the N and S by belts of thinly interbedded quartzite and schist containing an intense near-vertical transposition foliation. Within these belts the form-surface is only recognisable

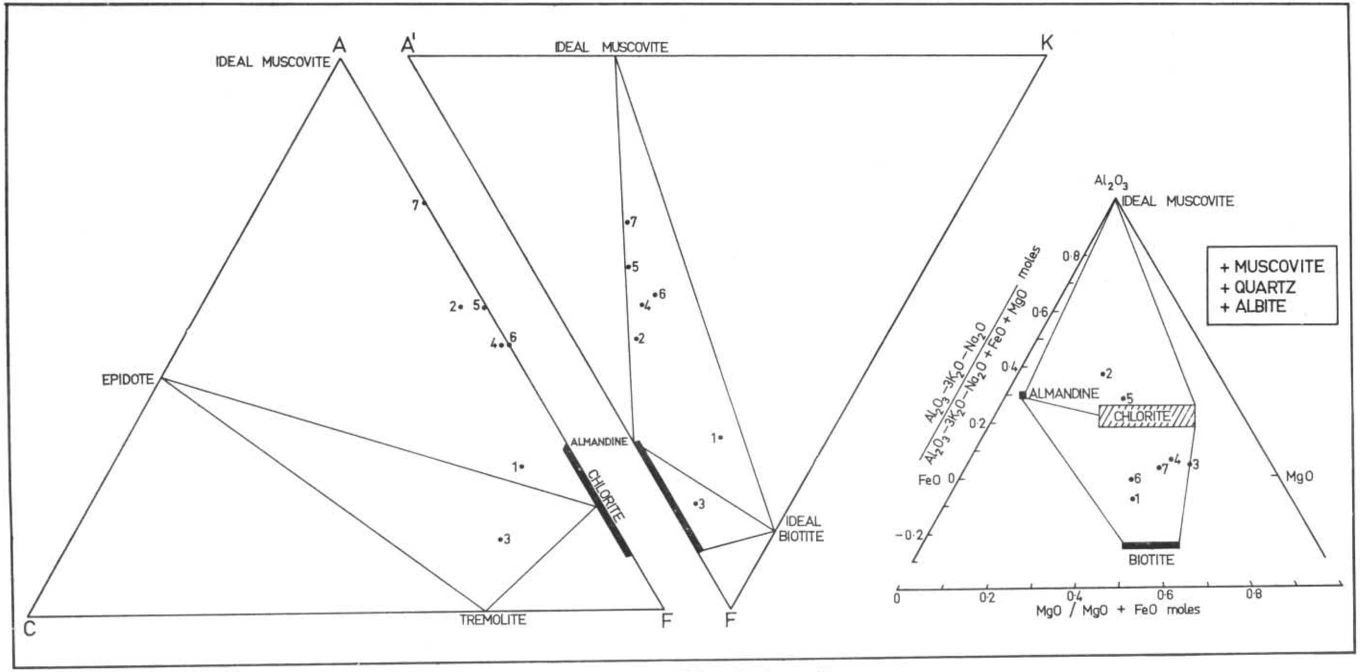

FIGURE 5. Metamorphic facies diagrams

5 cm

in small detached fold cores, quartz rods, and contorted and sliced shreds of the quartzite. The folds axes vary markedly in plunge, but have constantly orientated E.W axial planes.

In a sequence of quartzite, pelite and semi-pelite at Lake Rodway abundant folds in S_1 (and S_2) have developed an axial-plane strain-slip cleavage (S_3). Detached fold cores of quartzite occur within pelite, and folded mesoscopic folds are exposed at Flynns Tarn (1 km N of Lake Rodway). Figure 2f illustrates the style of refolding.

At Twisted Lakes (2 km N of Lake Rodway) a group of rather open folds with wavelengths of up to 200 m have S_2 as the form surface and have developed a strain-slip cleavage with an axial surface orientation (fig. 3f). These folds have variable but generally sub-horizontal plunges and steeply dipping E-W trending axial planes.

Hansons Peak, 1 km further N, is an antiformal mullion zone which plunges steeply to the WSW within a near-vertical axial plane (S_3). The mullions are bounded by S_1 (with S_2 co-planar), and the newly-generated, coarsely-spaced strain-slip cleavage S_3 (fig. 2e). Further evidence of refolding is visible in the schistose quartzite between the quartzite slabs. Minor folds with an axial surface schistosity (S_2) are discordant to and maintain a constant vergence relationship with, the layering of the main slabs around the antiform.

The major pelitic belt to the N of Waldheim, which includes the Mt Kate antiform, does not exhibit the intense transposition structures found further to the S. The S_2 foliation which defined the crest of the antiform is bent into broad open mesoscopic folds. Garnet schist at lower structural levels possesses a widespread but weak strain-slip cleavage, usually only visible microscopically. Its style (fig. 2c) may be compared with the stronger cleavage shown in Figure 3f. The S_3 cleavage in the garnet schist has a general E-W trend and is approximately vertical. In the phyllite at higher structural levels, S_2 itself an axial plane schistosity, is the form surface of open or moderately tight folds with an axial plane strain-slip cleavage (fig. 3e). These folds generally plunge at less than 30° to the WSW.

Late Structures

Regular accordian folds are common in the platy quartzite and semi-pelite in certain narrow NNW-SSE trending zones between Lake Rodway and Crater Lake. The folds are angular, symmetrical, with regularly spaced parallel axial planes averaging 40 cm apart. The axial planes trend NNW-SSE and the axes plunge steeply in the near-vertical foliation. They are entirely post-metamorphic, and deform all the structures previously described. In the Lake Rodway area especially at the overflow lip of Flynns Tarn, the folds occur in belts up to 30 m wide, in which the folding increases in intensity toward NNW-SSE trending faults. These faults, which are common in the Lake Rodway area, generally have a small displacement with a dextral strike-slip component. A similar trending fault at Granite Tor cuts and displaces Devonian granite; it is therefore possible that kinks are related to the Middle Devonian Tabberabberan orogeny which affected the Lower Palaeozoic rocks about 16 km to the NW.

Regional Structure

The regional structure (fig. 1) consists of a series of approximately vertical belts of pelite and quartzite with abundant internal folding. The only unit structure on this scale is the Mt Kate antiform.

The major lithological boundaries are variable in nature. The boundary between the schist belt at Waldheim and the thinner quartzite slab to the N is parallel to the S_1 bedding foliation. However, this same quartzite slap truncates the folded S_2-surface in the pelite to its N on the limb of the Mt Kate antiform. The lithological layering within the semi-pelite belt that extends from Granite Tor to Lake Rodway is truncated acutely by the major dislocation which, in the Lake Rodway area, appears to post-date both the F_1 and F_2 Precambrian folds. To the west of Lake Dove, the boundary between a thin pelite bed and major quartzite slabs on either side can be related to the thrusting out of the limbs of the F_2 folds. Similar types of dislocation, clearly related to F_2 folds, occur in the area between Lake Dove and Twisted Lakes. In the SE corner of the map area (fig. 1) gently folded massive quartzite abuts a zone of intensely transposed vertically dipping schistose quartzite.

The Mt Kate antiform is an asymmetrical structure, with an approximate SW plunge of 30°, a gentle northerly limb which tends to become synformal, and a steep southern limb. The southern limb is marked by a major dislocation which truncates abruptly the metamorphic zoning and the S_2 foliation. The Mt Kate antiform may therefore be thought of as an undeformed remnant of an early, more or less flat-lying basement, rather than as a late antiform formed by rotation of the steeply dipping foliation to horizontal.

Conclusions

The sequence of events in the evolution of the Precambrian basement in the Cradle Mt area may be summarised as follows: The earliest recorded event was the growth of muscovite and chlorite along the bedding of orthoquartzite and siltstone to produce a bedding foliation. This event culminated in the growth of pre-kinematic almandine garnet, although garnet did extend into the early syn-kinematic phase of F_1. The main period of F_1 folding was accompanied by the formation of a widespread axial plane schistosity in the pelites due to the syn-kinematic growth of muscovite, biotite and chlorite. The basic dyke was intruded at about this stage, and appears to have undergone syn-kinematic retrogressive metamorphism. Muscovite and chlorite continued to grow in the post-tectonic interval. Albite was the last metamorphic mineral to crystallise in the inter-kinematic period between F_1 and F_2.

The F_2 movement was essentially a post-metamorphic slicing of the basement along near vertical, E-W trending shear zones. The more strongly transposed zones may have been controlled by the distribution of pelitic belts, but at this stage of the investigation the nature of the F_1 structure, and consequently its influence on the F_2 structures is not known. The F_2 movement and the S_3 cleavage was not accompanied by the formation of any new metamorphic minerals but was merely associated with the recrystallisation of quartz and the minor growth of muscovite and chlorite.

The Mt Kate antiform is interpreted as a flat-lying remnant of the metamorphic basement in which is preserved a zonal sequence grading from low-grade metasediments to upper greenschist facies. Using a plunge correction of 30° W for the antiform, the vertical tectonic thickness exposed is in the order of 7 km. This would correspond approximately with a pressure of two kilobars, a figure compatible with the pressure range of the greenschist facies (Turner, 1968).

There are basic similarities and important differences between the sequences in the Cradle Mt area and those in other parts of the Precambrian basement. The sequence at Raglan Range (Gee, 1963) and Frenchmans Cap (Spry, 1963a) is summarised in Figure 6a. At the Raglan Range the earliest and main period of metamorphism (M_1) started earlier and finished later than the first period of deformation (F_1), and involved the growth of chlorite, biotite, almandine and kyanite in an approximate zonal sequence. The overlapping nature

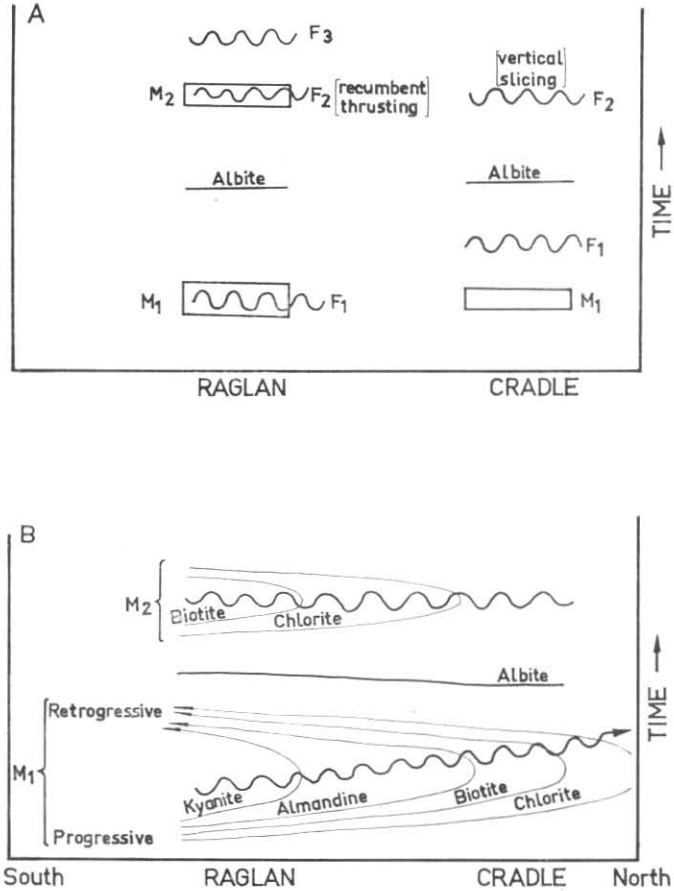

FIGURE 6. A: Comparison of structural and metamorphic sequences
B: Suggested time paths for the components of the Frenchman orogeny

5 cm

of biotite, muscovite and chlorite is probably the retrogressive phase of M_1. The syn-metamorphic nature of F_1 is revealed by the presence of syn-kinematic rims on idioblastic cores of almandine and idioblastic rims on syn-kinematic cores. Isolated F_1 fold cores are present on the Raglan Range (Gee, 1963, plate 1b). These events were followed by the growth of inter-kinematic albite which preserved helicitic inclusions of contorted S_1. A second period of metamorphism (M_2) involved the growth of muscovite, biotite and chlorite: this was coeval with a major period of recumbent folding and thrusting (F_2) probably involving nappes (Spry, 1963b). The latest event at the Raglan Range was a non-metamorphic development of a late cleavage (S_3).

The textural analyses of Spry (1963b) from widely scattered parts of the Precambrian basement indicate that the two-phase deformation, with the main metamorphism approximately coeval with F_1, is a basic pattern for the Frenchman orogeny, and forms a basis for the regional correlation of the components.

The sequence at Cradle Mt differs (fig. 6a) from that in the Frenchmans Cap area because of the appearance of the M_1 climax before F_1, the incipient effects only of M_2, and the F_2 vertical slicing as distinct from recumbent thrusting. These differences probably represent the diachronous and independent behaviour of the component events of an orogenic period as envisaged by Johnson (1963) in the British Caledonides and den Tex (1963) in the Alps. Den Tex postulated that in an orogenic belt, metamorphism dies out toward the central axial region, whereas deformation dies out away from the axial region. It should be possible to represent the time-paths of the components on a three-dimension model (geographical co-ordinates and time) for a given tectonic level.

A two-dimensional model for the Frenchman Orogeny, from N to S is shown in Figure 6b, and may explain the differences in the sequences. In this model the metamorphic time-lines are based on the assumption that metamorphism expands away from (progressive), and contracts towards (retrogressive), a central axial region. The bulk metamorphic path can be split into the component isograds, with the lower grade curves enveloping the higher grade curves. The F_1 deformation appears to be diachronous with respect to the climax of M_1, and the central region lies somewhere to the S. This model, however, will require testing by detailed investigations in many other parts of the Precambrian metamorphic basement.

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