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Deformation history of the Otago schists, New Zealand, from progressively developed porphyroblast-matrix microstructures: uplift-collapse orogenesis and its implications

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Abstract—Foliation overprinting relationships preserved in porphyroblasts and the surrounding matrix in the Otago schists indicate development of up to six penetrative foliations during the late Paleozoic–Mesozoic Rangitata Orogeny. S_1, S_3 and S_5 formed with steep dips, and S_2, S_4 and S_6 formed with gentle dips.

S_1 and S_2 are preserved only as inclusion trails in porphyroblasts because of matrix-foliation reworking during progressive deformation. S_3–S_6 are preserved in the matrix as well as in porphyroblasts, and are generally correlatable from one to the other. Inclusion-trail asymmetries define the location of the orogenic uplift core during the Rangitata Orogeny when the porphyroblasts grew. The location of this core is consistent with macroscale geological and structural observations.

Alternating steep and gently dipping foliations are inferred to indicate alternating horizontal compression and extension. Predictions made by an orogenic model compatible with continually alternating horizontal compression and extension compare favorably with geometries observed in the schists.

Reconstruction of the gross geometry of the Otago schists during the Rangitata Orogeny, based on the three-dimensional geometry of porphyroblast inclusion trails, is similar to reconstructions based on regional geological considerations and plate tectonic calculations.

INTRODUCTION AND GEOLOGICAL SETTING

THIS paper discusses the deformation history of the Otago schists, New Zealand (Fig. 1), based on a detailed analysis of progressively developed porphyroblast and matrix microstructures. The Otago schists are part of the Haast Schist Terrane (Coombs *et al.* 1976), which forms an arc of medium- to high-grade metamorphic schists extending from Marlborough in the northeast (Marlborough schists), southwards in a narrow zone along the Alpine Fault and Southern Alps (Alpine schists), spreading southeast into a much broader region across Otago (Otago schists; Fig. 1). The rocks used in this study were collected mainly in the Otago schists, with some coming from the southern Alpine schists.

The Haast Schist Terrane is generally accepted as having formed during the late Paleozoic–Mesozoic Rangitata Orogeny, with parts of the schist belt having been further deformed during the late Cenozoic Kaikoura Orogeny (e.g. Findlay 1987, Kamp 1987). However, the extent of the effects of post-Rangitata deformation and metamorphism is not fully understood.

The Otago schists, some 30,000 km^2 in extent, consist mainly of pelitic and psammitic schists, with traceable horizons of metavolcanic rocks or greenschists commonly occurring throughout northwest Otago (Craw 1984, 1985). The schists grade from amphibolite metamorphic facies in the northwest, to prehnite–pumpellyite facies on their southwest and northeast margins, with the largest extent of the schist belt in the greenschist facies of metamorphism (Landis & Coombs 1967). The belt is bounded by the Alpine Fault to the northwest, the Caples Terrane and Livingstone Fault to the southwest, the Torlesse Terrane to the northeast, and crosses the east Otago coast near Dunedin (Figs. 1 and 2).

Many studies have been devoted to structural analysis of portions of the Otago schists (e.g. Grindley 1963,

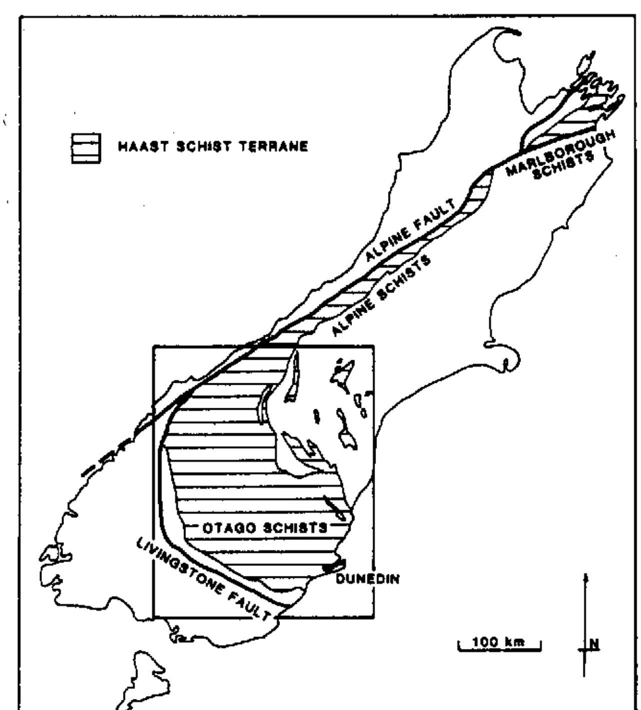

Fig. 1. South Island, New Zealand, showing location of Haast Schist Terrane. Rectangle outlines area detailed in Figs. 2, 9 and 10.

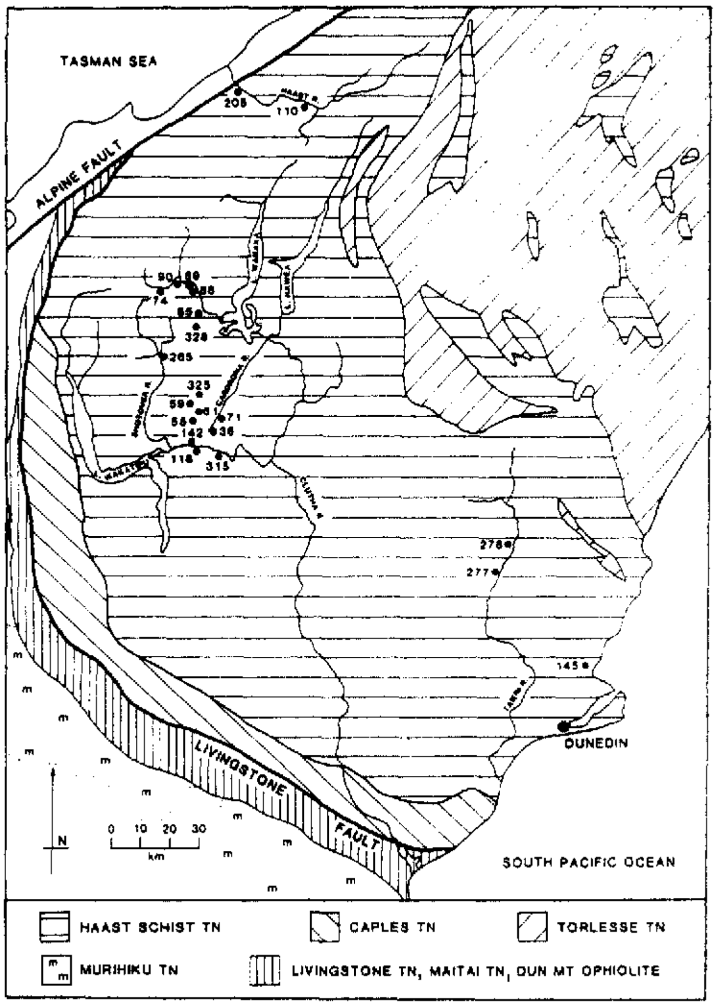

Fig. 2. Geology of area outlined in Fig. 1, showing locations of porphyroblastic samples used in this study.

Wood 1963, 1978, Means 1966, Cooper 1974, Bishop *et al.* 1976, Norris & Cooper 1977, Turnbull 1981, Craw 1985). Wood (1963) presented the first generalized geometric interpretation, supporting earlier suggestions made by Benson (1921) and Macpherson (1966), that the Otago schists are a stack of recumbent and reclining, thrust-related, nappe-like folds, flanked to the northeast and southwest by reclined isoclinal folds. Further detailed studies have provided a general confirmation of this geometric interpretation (e.g. Means 1966, Brown 1968, Norris & Cooper 1977, Wood 1978, Turnbull 1981, Craw 1985), though the progressive structural development of the belt remains unclear. Most detailed studies have recognized similar features including two or three early stages of ductile deformation associated with the development of major nappe-like structures, followed by two or three stages of brittle deformation. Though some elements of the deformation history appear to be similar from one area to another, direct correlation of deformation events has not been accomplished with any certainty (e.g. Craw 1985). Because the Otago schists are difficult to analyse fully at the meso and macro scales, and because they contain garnet and plagioclase porphyroblasts, they provide a good setting for microstructural analysis.

MICROSTRUCTURAL ANALYSIS

Introduction—use of pophryroblasts in structural analysis

Porphyroblast microstructures, where inclusion trails are present, have consistently yielded significant information about the structural–metamorphic history of orogenic belts (e.g. Fyson 1980, Bell & Brothers 1985, Steinhardt 1988, Vernon 1988, Bell & Johnson 1989). There is now considerable evidence that porphyroblasts do not generally rotate relative to geographic coordinates during ductile deformation, provided they do not deform internally (e.g. Fyson 1980, Bell 1985, Bell *et al.* 1986, Vernon 1988, Steinahrdt 1988, Bell & Johnson 1989, Johnson 1990). This means that the orientations of foliations preserved as inclusion trails (S_i) within porphyroblasts may be indicative of their original orientations at the time of porphyroblasts growth, even though the rock may have undergone subsequent, intense, non-coaxial deformation.

Recently, Bell & Johnson (1989) have shown that this is true even for classic 'snowball' garnet porphyroblasts, such as those described by Rosenfeld (1968), Schoneveld (1977) and Powell & Vernon (1979). The spiral-shaped and other complexly-shaped S_i in these and other porphyroblasts can be explained by successive overprinting of near orthogonal foliations, and their orientations and overprinting asymmetries can be used to elucidate parts of a deformation history no longer preserved in the surrounding matrix (e.g. Steinhardt 1988, Bell & Johnson 1989).

The effects of high-level faulting and flexural folding on the orientations of porphyroblasts are presently unknown, although it may be reasonable to assume that brittle faults with a rotational component of displacement locally disturb them. How local this effect is remains to be determined.

Method—sample and thin section preparation

All samples collected from the schist belt were oriented, and at least two vertical thin sections were made from each rock: one parallel to the length of the belt in Otago (NW–SE), and the other perpendicular to it. Thus all thin sections were oriented the same way relative to the gross geometry of the belt.

If a rock was found to contain porphyroblasts with S_i, it was reoriented, and the faces from which the thin sections came were marked with horizontal lines, barbed to show direction down, which were then transferred to the thin sections. Obliquely-oriented thin sections were then cut to allow correlation of the foliations defined by the S_i, and hence, their orientations in three dimensions.

At least two thin sections were cut for each orientation to obtain enough porphyroblasts containing a major portion of the structural history; only a porphyroblast sliced through its center will contain all preserved stages of foliation development, whereas one sliced through its rim will only show the youngest stages. More thin sections were used where the porphyroblasts were large or few in number.

Deformation history preserved in porphyroblasts and matrix

Porphyroblasts and matrix microstructures from the Otago schists preserve multiple foliations that successively overprint one another, providing a detailed history of progressive structural development. Examination of more than two thousand porphyroblasts with well-developed S_i, from the 21 sample localities shown in Fig. 2, indicated that S_i geometries (from these localities) generally fall into one or more of six groups: (1) steep S_i that are straight or sigmoidal, and commonly continuous with a gently dipping foliation (S_e) directly adjacent to the porphyroblast (Fig. 3a); (2) gently dipping S_i that are straight or sigmoidal (Fig. 3b), and commonly continuous with a steep S_e directly adjacent to the porphyroblast; (3) steeply and gently dipping S_i that have interpretable overprinting relationships (Bell & Johnson 1989), where the last set of overprinting S_i is commonly continuous with an orthogonal, steeply or gently dipping S_e adjacent to the porphyroblast (Figs. 3c & d); (4) variously oriented S_i resulting from late porphyroblast growth over tightly folded and/or crenulated S_e, where the axial planes of the folds and or crenulations are steep and/or gently dipping (Fig. 4a); (5) S_i significantly oblique to the vertical and horizontal, and continuous with, and commonly parallel to, S_e (Fig. 4b); and (6) folded S_i continuous with S_e that has been overgrown by very late porphyroblasts (Fig. 4c).

Three points about the above six geometry groups can be made that have direct significance for the deformation history of the schist belt.

(i) The majority of observed geometries fall into groups (1)–(3) above. This means that newly developing foliations, at locations in the orogen where porphyroblasts could overgrow them, had steep and/or gentle dips. The preservation of steep and/or gently dipping foliations within the majority of porphyroblasts examined has been found in a number of other orogenic belts (e.g. Bell & Johnson 1989 and unpublished data from the Pyrenees, Steinhardt 1988, 1989, T. H. Bell unpublished data from the Appalachians, B. K. Davis unpublished data from North Queensland, Australia, N. Hayward unpublished data from the Appalachians, C. Wilkins unpublished data from the Archean of Western Australia).

(ii) A sensible interpretation of geometry (5) can be found by examining the timing relationships between those porphyroblasts with geometries (1)–(3), and those with geometry (5). Figure 4 (d) shows several porphyroblasts with steep S_i, and a gently dipping crenulation cleavage in parts of the matrix. The crenulation cleavage is progressively dextrally rotated and decrenulated during reactivation (Bell 1986), resulting in an oblique reactivated foliation in areas of relatively high progressive shearing strain. The one porphyroblast in Fig. 4(d) (large, tabular porphyroblast in the bottom-right of the photomicrograph) that exhibits geometry (5) above has grown over this reactivated foliation, and represents the latest porphyroblast growth stage in this rock. These porphyroblasts that overgrow the reactivated foliation generally have a tabular shape (Fig. 4b), and their later timing is demonstrated in part by the smaller angle between S_i and S_e compared to the surrounding porphyroblasts. This smaller angle between S_i and S_e is always the case, even when these porphyroblasts have more equant shapes.

Thus, porphyroblasts with this S_i geometry (and also those with geometry 6–timing relationships between porphyroblasts with geometries 5 and 6 could not be determined) appear to be the last ones to have grown in any particular rock, and they grew over a foliation that was already significantly oblique to the vertical and horizontal.

(iii) Geometry (3) above is quite common, and provides asymmetry relationships between overprinting foliations trapped within the porphyroblasts. Bell & Johnson (1989) have shown that spiral-shaped and other complex S_i can be a product of successive overprinting of near-orthogonal foliations (see fig. 20 in Bell & Johnson

1989). Their model for the formation of spiral-shaped inclusion trails is further supported by this study. Steinhardt (1988) has described rocks that contain andalusite porphyroblasts with spiral-shaped and other complex S_i with the same steep and gentle dips shown herein and in Bell & Johnson (1989).

To form a perfect spiral, all the successively developed foliations must overprint with the same asymmetry (see fig. 20 in Bell & Johnson 1989). Where variations in the asymmetry of overprinting foliations occur, inclusion trail geometries show these changes. For example, the albite porphyroblast in Fig. 5(a) preserves three near-orthogonal foliations as S_i, and one on its margins. Note also that the overprinting asymmetries of foliations (4) and (5) are sinistral, whereas the overprinting asymmetry of foliation (6) is dextral. Note the well-developed truncations that occur between the different generations of S_i (see Bell & Johnson 1989, for a detailed discussion of these truncations). A fifth, weakly-developed foliation significantly oblique to the vertical and horizontal appears in the matrix, and is interpreted to be a product of foliation reactivation (Johnson 1990). Late-stage porphyroblasts occasionally overgrow this foliation resulting in geometry (5) discussed above (Figs. 4b & d).

Figure 5(a) shows the deformation history preserved at location 315 (see Fig. 2). The microstructural history was determined for each of the locations in Fig. 2 from progressively developed porphyroblast and matrix microstructures. Fig. 6 shows these histories, looking northwest along the length of the Otago belt, for those localities shown in Fig. 2. Wheras most areas show development of at least three separate, near-orthogonal foliations, several locations show more. The maximum number of overprinting foliations preserved at any location was six (locations 71 and 265, Fig. 6). S_6 in these samples corresponds to the last pervasive foliation present at the meso scale. In many cases, this foliation is flat-lying, and is used here as a marker for correlating deformation histories from location to location. The foliations in Fig. 6 were numbered inward from this easily recognizable, pervasive S_e.

For most of the locations in Fig. 2, the total histories shown in Fig. 6 can be found in numerous individual porphyroblasts (e.g. Fig. 5a). At other locations this history was pieced together from various growth stages of albite porphyroblasts preserving different parts of the deformation history. In several samples, conflicting asymmetries were present for the same overprinting event; however, in all cases one assymmetry was clearly dominant over the other, and this dominant asymmetry was the one chosen as representing the asymmetry of the sample as a whole during that overprinting event.

Late kink-folds and crenulations are present in some samples, but are not included in Fig. 6. These structures clearly post-date S_1–S_6, but their relative timing was not determinable because overprinting relationships between the two were never observed. The relative timing of these two structures was determined mesoscopically by Craw (1985), and will be discussed later. These kinks and crenulations, based on the relative timing determined by Craw (1985), are labelled F_7 and F_8, respectively.

Foliation overprinting mechanisms

Foliation overprinting in the Otago schists is most commonly accommodated in two ways. The first involves crenulation cleavage formation (Bell & Rubenach 1983). The second involves reactivation, with associated rotation and decrenulation (e.g. Fig. 4b) (Bell 1986). This generally occurs when the overprinted foliation is a crenulation cleavage no further than stage 3 or 4 of crenulation cleavage development (Bell & Rubenach 1983).

These overprinting mechanisms commonly involved a degree of progressive rotation of the foliation, and nucleation of a crenulation-type geometry around heterogeneities such as porphyroblasts. If further growth of the porphyroblast occurs, the overprinting asymmetry of the crenulation-type geometry may be preserved as S_i (see fig. 20 in Bell & Johnson 1989).

The reliability of foliation orientations in low-strain zones and porphyroblasts is relatively high, and it is suggested that orientations oblique to these are commonly a product of foliation reactivation and/or rotation during progressive deformation (e.g. Platt 1983, 1984, Bell 1986, Behrmann 1987, Bell & Johnson unpublished data).

Determining the strike of steep inclusion trails

Where S_i geometries were simple and steeply dipping, their strike was easily measured in horizontal thin sections. Where simple S_i were gently dipping, but had curvature at the margins of the porphyroblast, the strike, at time of formation, of the overprinting steep S_e was determined as follows. Differently oriented vertical thin sections were cut until a complete asymmetry change was observed (compare the asymmetry of faces 1 and 2 with face 3, Fig. 7a). A line was drawn bisecting the obtuse angle between the two nearest cut-faces showing this asymmetry change (faces 2 and 3, Fig. 7a). The direction perpendicular to this line closely approximates the strike of the steep S_e that overprinted the shallow S_i in the porphyroblast.

Where S_i geometries were complex, numerous thin sections were cut until a consistent reversal in the asymmetry of overprinting S_i was observed. It is important that when asymmetry change was achieved, it was *complete* for all porphyroblasts in a given thin section. Again, a perpendicular line to the bisector of these two faces represents the approximate strike of steep S_i (Fig. 7b). This technique was rarely used, because porphyroblasts with relatively simple trails were generally present.

After the approximate strike was obtained using this method, horizontal thin sections were examined. In samples where steep S_i were present in porphyroblasts, well-defined S_i were present in horizontal sections, and

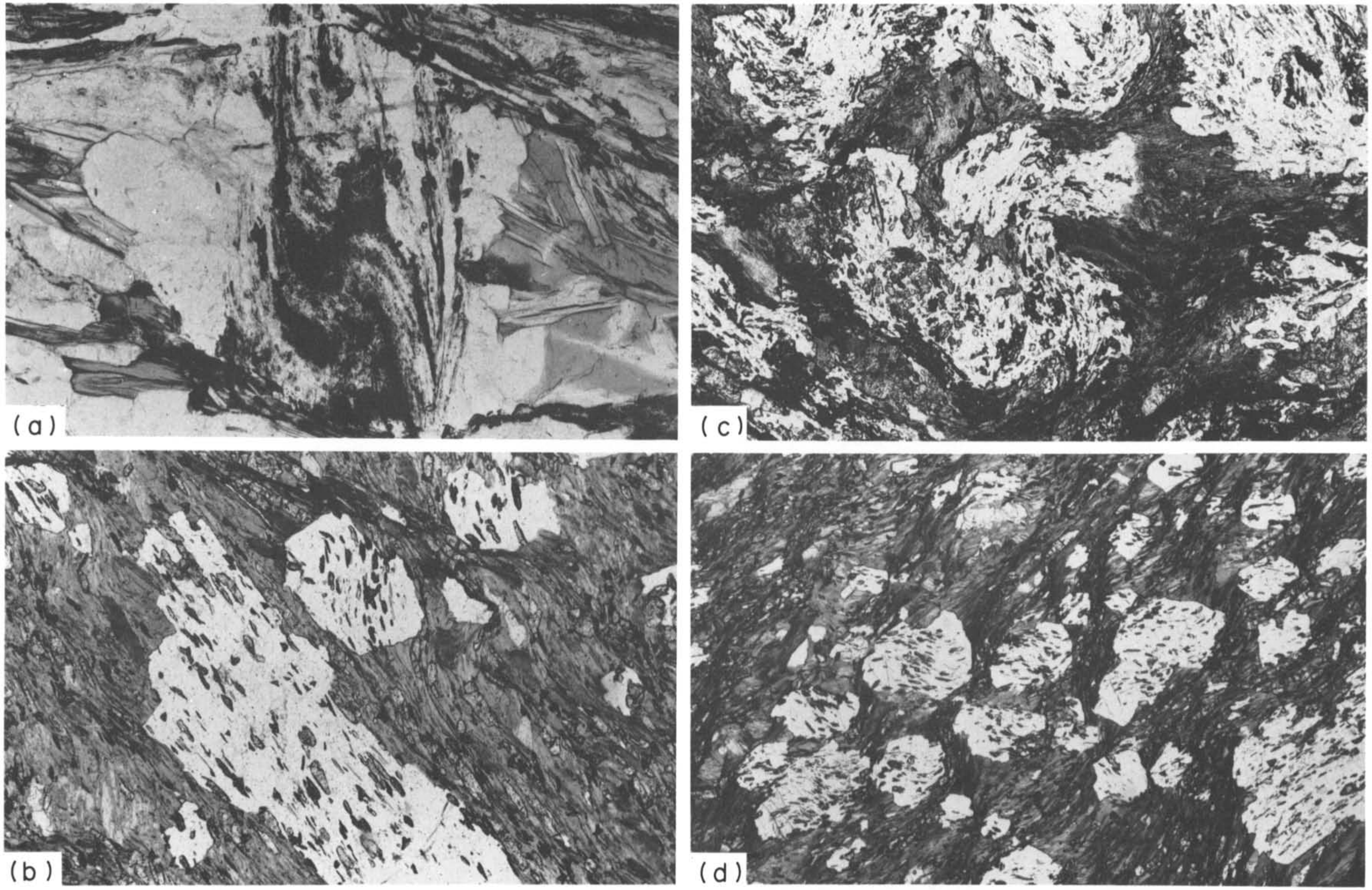

Fig. 4. (a) S_i in albite porphyroblast folded about steep axial planes. S_e is gently dipping. Vertical thin section; plane polarized light; long axis horizontal, 2.1 mm. (b) Oblique S_i in elongate albite porphyroblast as a result of porphyroblast growth over reactivated foliation. Note the two porphyroblasts to the upper right of main porphyroblast that have steep S_i. Note preserved gently dipping crenulation cleavage to the lower left of main porphyroblast. Vertical thin section; plane polarized light; long axis horizontal, 2.1 mm. (c) Late albite porphyroblasts that have overgrown complexly folded S_e. Note S_i and S_e are continuous. Vertical thin section; plane polarized light; long axis horizontal, 2.1 mm. (d) Photomicrograph showing albite porphyroblasts with steep S_i, which grew during the development of a gently dipping crenulation. This crenulation has been rotated and decrenulated during reactivation, resulting in a foliation significantly oblique to the vertical and horizontal. A late-stage porphyroblast (large porphyroblast at lower-right) has overgrown this oblique foliation (compare Fig. 4b). Vertical thin section; plane polarized light; long axis vertical, 4.1 mm.

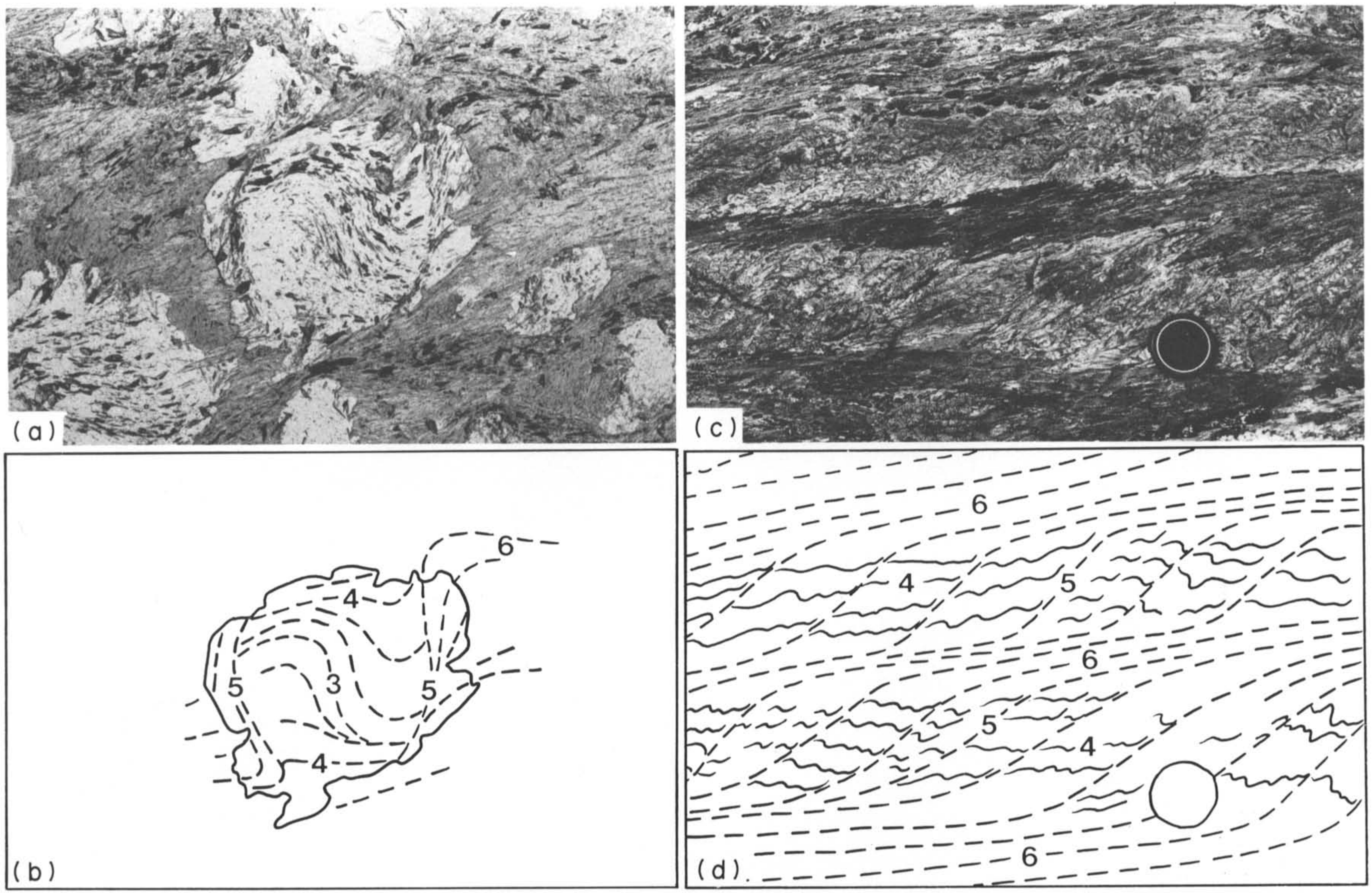

Fig. 5. (a) Photomicrograph of albite porphyroblast with four different foliations preserved as inclusion trails. S_3 and S_5 are steep, and S_4 and S_6 are gently dipping. S_6 in the matrix has been re-oriented by reactivation into an oblique orientation, as seen to the left and upper left of the porphyroblast. Vertical section; plane polarized light; long axis horizontal, 2.1 mm. (b) Line diagram of (a). (c) Crenulation cleavage (S_5) in quartz-rich layers has been progressively dextrally rotated into a gently dipping orientation (S_6) in surrounding micaceous layers. The dip of the crenulation cleavage within the quartz-rich layers varies depending on the amount of shearing (rotational) strain partitioned into the layer. The crenulation cleavage is interpreted as having formed with a steep dip. Photograph looking northwest; base horizontal; lens cap 5.5 cm in diameter. (d) Line diagram of (c).

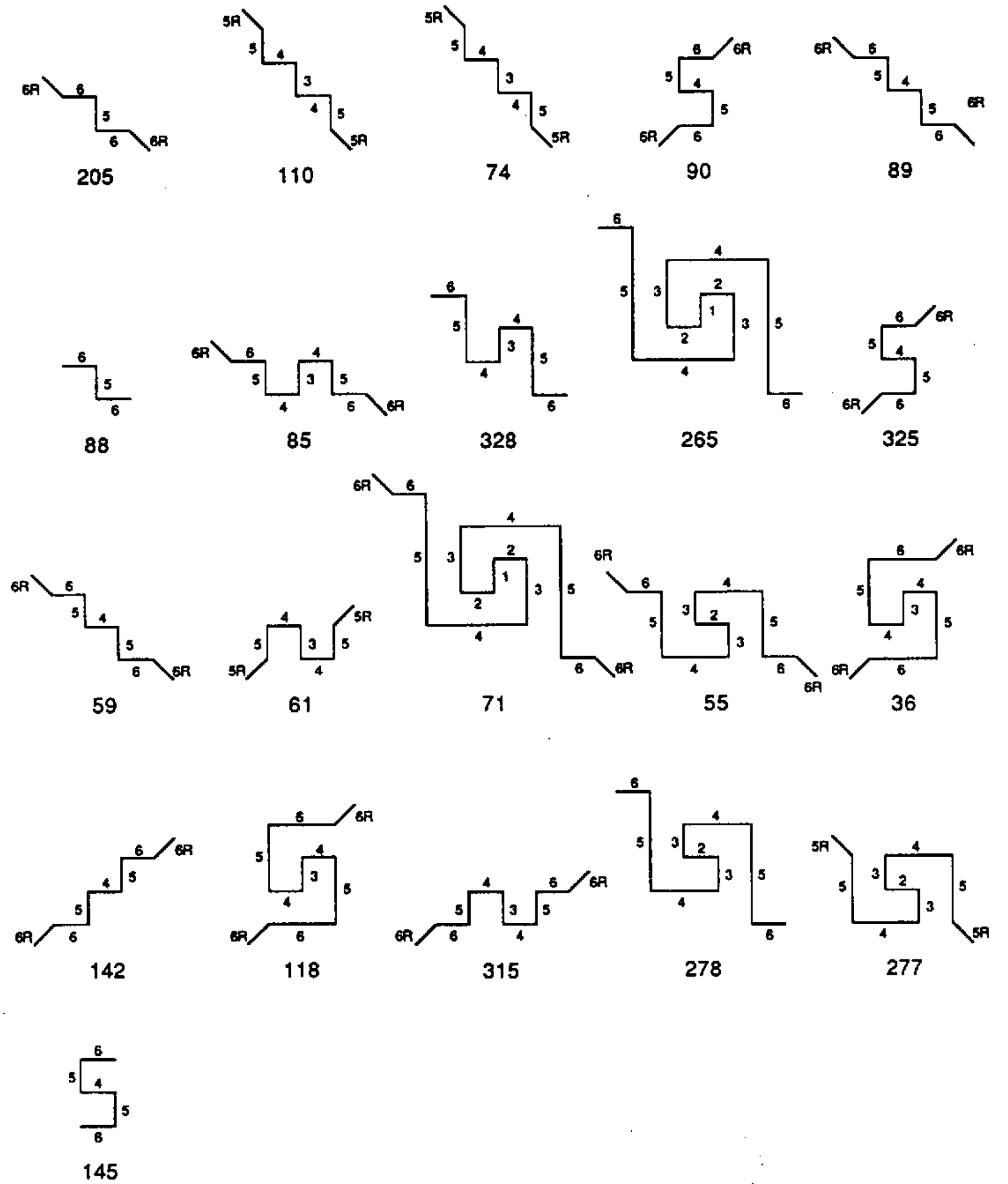

Fig. 6. Schematic diagrams showing the total preserved microstructural history of foliation formation for those locations shown in Fig. 2. Where an 'R' appears after a foliation number, this signifies an oblique foliation formed by rotation or re-activation, possibly during a final, incompletely developed overprinting event. For clearer understanding, compare the diagram from location 315 with the albite porphyroblast from location 315 shown in Fig. 5(a).

were oriented subparallel to the previously determined approximate strike direction (Fig. 7b). In samples where only gently dipping S_i trails were present in porphyroblasts, well-defined S_i were seldom seen in these horizontal thin sections because the plane of the section was subparallel to the S_i surface. However, where inclusion trails were observed, they were consistently oriented approximately perpendicular to the strike direction determined for the steep trails (Fig. 7a). Because the intersection lineation of two nearly coincident planes is subject to marked variation with small variation in plane orientations, these consistently-oriented, but poorly-developed inclusions are interpreted as mineral elongation lineations on the shallow S_i surfaces, rather than the intersection of the S_i surface with the thin section.

In porphyroblasts with overprinting S_i, gently dipping S_i trails were seldom seen in horizontal thin sections. Where they were present, they were consistently oriented approximately perpendicular to the steep S_i and in this case were interpreted as either (1) a mineral elongation lineation on shallow S_i, or (2) intersection of the gently dipping S_i with the horizontal thin section surface, at a moderate to high angle, because the developing gently dipping foliation wrapped around a pre-existing porphyroblast core before the next porphyroblast growth-stage preserved the foliation as S_i.

Using these techniques, numerous measurements were made of the strike of steep S_i and steep S_e adjacent to porphyroblasts with shallow S_i, in horizontal thin sections, and these measurements were compiled into rose diagrams (Fig. 8). From these rose diagrams, it is clear that there are three orientation-domains within the study area. For convenience, these domains will be referred to as the NW, central and SE domains (see Fig. 2). S_i in the NW domain are simple and generally poorly developed. Therefore, little information was obtained about their development other than the strike of steep S_e in two specimens (Fig. 8). From the central domain, many specimens contained porphyroblasts with well-developed S_i that, in most cases, provide asymmetry information about three or more foliations. From the SE domain, three specimens contained useful microstructural information. The consistency of strike in each domain suggests both lack of porphyroblast rotation (Johnson 1990) and that the orientation in each domain indicates the regional trend of the belt at the time the measured steep foliations (generally S_5) formed, as discussed later.

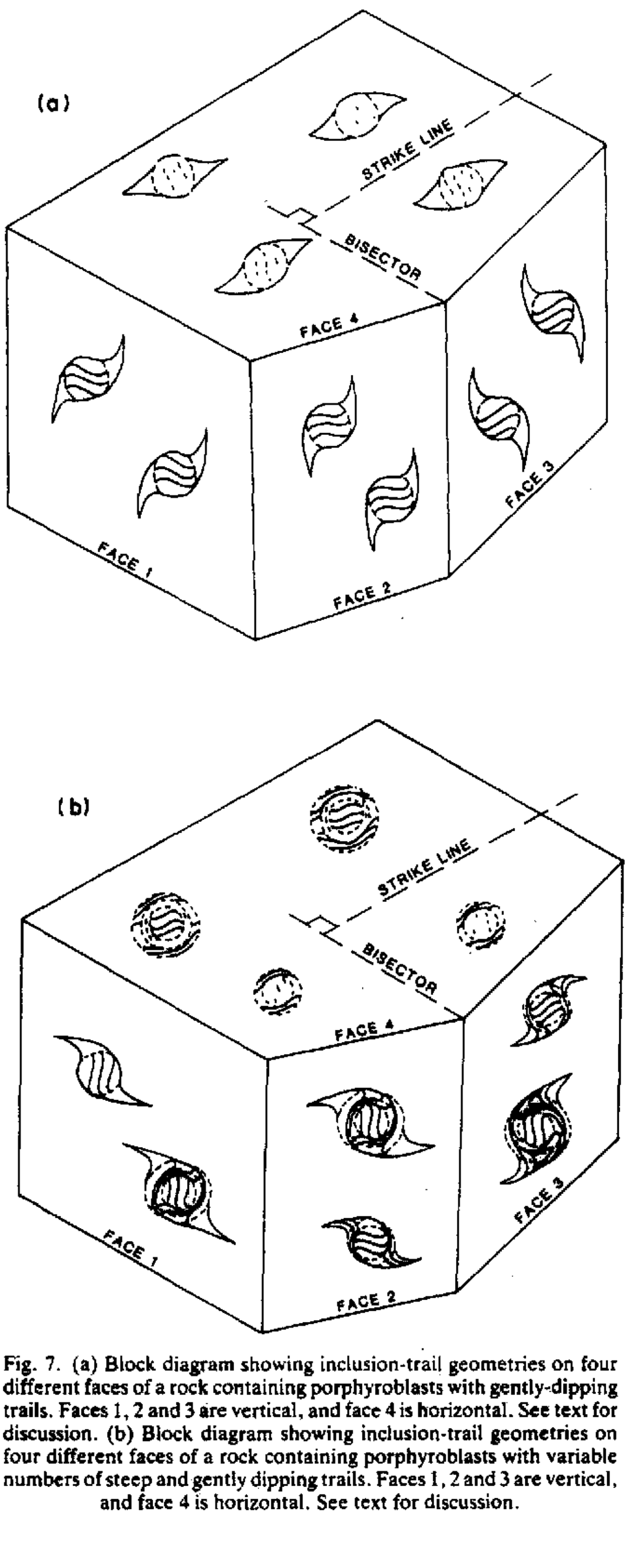

Fig. 7. (a) Block diagram showing inclusion-trail geometries on four different faces of a rock containing porphyroblasts with gently-dipping trails. Faces 1, 2 and 3 are vertical, and face 4 is horizontal. See text for discussion. (b) Block diagram showing inclusion-trail geometries on four different faces of a rock containing porphyroblasts with variable numbers of steep and gently dipping trails. Faces 1, 2 and 3 are vertical, and face 4 is horizontal. See text for discussion.

Two further observations can be made from Fig. 7 that are critical to understanding the three-dimensional geometry of inclusion trails. These observations are also critical to understanding the geometric development of the schist belt, and will be discussed later in this context.

(1) Complete asymmetry changes between nearly parallel cut faces, where several sets of alternating, nearly orthogonal S_i were present, means that fold axes associated with steep *and* gently dipping S_i were consistently oriented from overprinting event to overprinting event. *Both sets* of fold axes were subparallel to the strike of steep S_i at the time of porphyroblast growth (Fig. 8). This was only verified in the central domain, where several locations contained porphyroblasts with well-developed overprinting S_i.

(2) Complete asymmetry changes were occasionally observed from porphyroblast to porphyroblast in a single horizontal thin section, where porphyroblasts contained several overprinting S_i. This indicates that the fold axes associated with the steep *and* gentle dipping S_i were gently double-plunging, or anastomosing, around the horizontal at the time of porphyroblast growth.

MESOSTRUCTURAL ANALYSIS

Meso scale structures in the Otago schists also show the results of multiple foliation overprinting. As with the matrix microstructures, less structural history is preserved compared to that in the porphyroblasts, due to the effects of foliation overprinting during progressive deformation.

At the outcrop scale, foliation orientations are variable, and generally oblique to the steep and gentle dips found in porphyroblasts. Some areas of the belt have a well-developed, flat-lying foliation, others have a well-developed, steeply-dipping foliation, and still others have complex orientations and relationships. These different orientations are commonly exposed in close proximity to one another making structural interpretation and correlation difficult.

Because of the problem this presents for structural geologists working in the field, it is necessary to look for key outcrops that preserve several overprinting foliations and their orientations. One very useful criteria in the Otago schists is the occasional occurrence of 'refracted' foliations (Fig. 5c). Figure 5(c) preserves the orientations, asymmetries and timing relationships of three

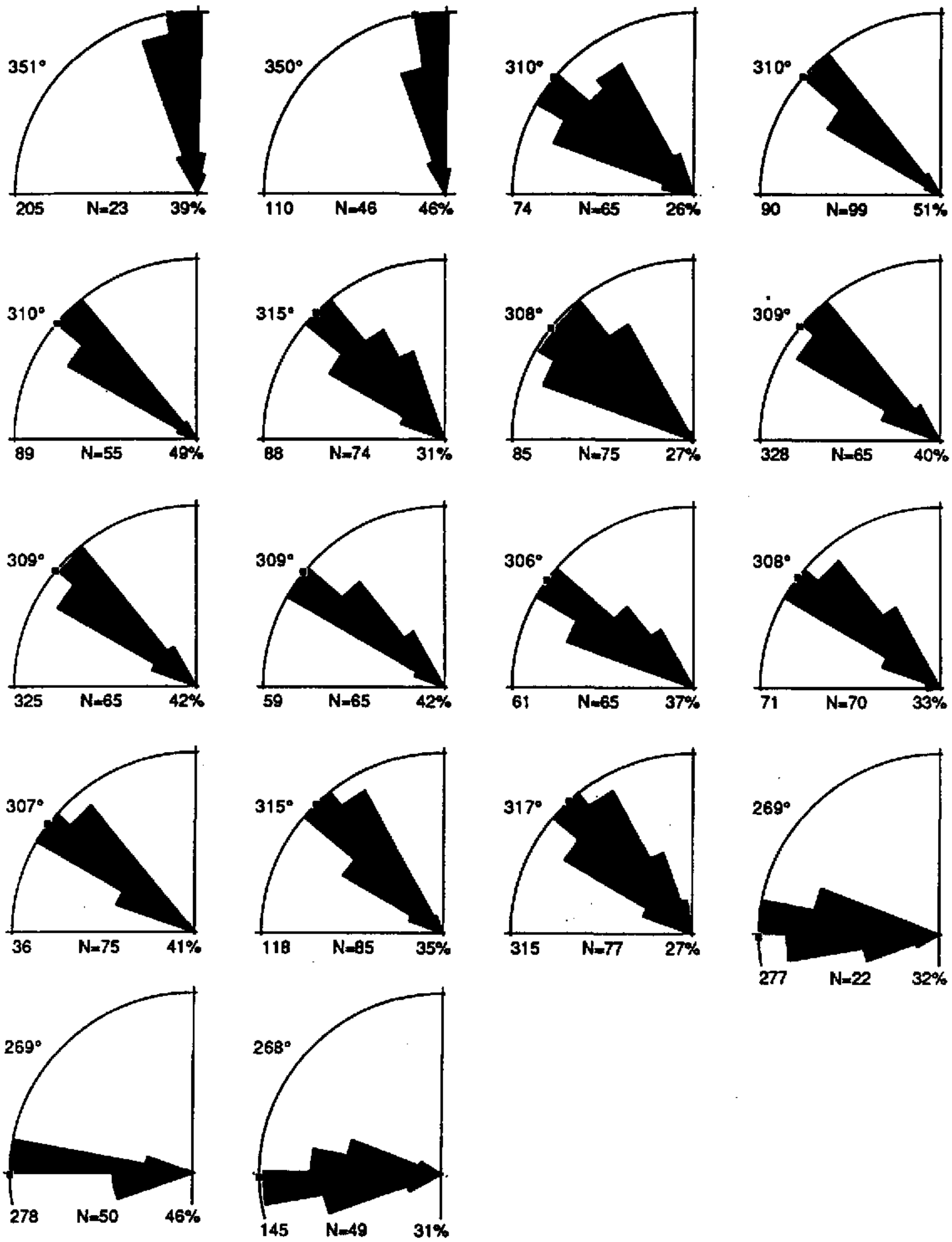

Fig. 8. Rose diagrams showing the strike of steep inclusion trails measured from horizontal thin sections. For each rose diagram, the mean vector is given at the upper left, the location number at the lower left, the number of measurements at the bottom center and the value of the largest petal at the lower right. Petals are in 10° increments.

separate foliations. S_6 corresponds to the main gently dipping foliation present throughout this area of the Otago schists. Note that even though S_5 has rotated completely into S_6 at the margins of the quartz-rich layer, it has a steep orientation within parts of the layer. In the well-foliated rocks surrounding these layers, there is little evidence for the two previously-formed foliations. At the micro scale, an early foliation (S_3) is present that pre-dates S_4, and overprinting criteria confirm the relative timing of S_5 and S_6.

Pillow lavas may also provide the competency contrast required to preserve earlier structures. Craw (1985) described pillow lavas on Mount Avalanche as preserving 'F_t' folds from the effects of later deformation.

Locally-developed, angular kink-folds that overprint S_6 were observed at the outcrop scale, and are correlated with F_7 kink-folds observed in thin sections. These kink-folds do not generally have an axial plane cleavage in central and northwestern Otago, and are commonly found associated with thrust faults.

Table 1. Correlation table showing how the structures recognized in this study correlate with those found in other structural studies of the Otago schists. Structures S_1–S_3 of this study have no correlative counterparts

	Regions of previous structural studies*						
This study	Aspiring	Caples	Hawea	Cromwell	Haast	East Otago	Copland
S_1–S_3							
S_4	D_1		F_1	F_1		F_1	
		F_1					
S_5	D_2			F_2	F_1	F_2	
			F_2				
S_6	D_3	F_2		F_3	F_2	F_3	D_2
Kink-folds (F_7)	D_4	F_3	F_4	F_4	F_3		D_3
Crenulation (F_8)	D_5		F_5		F_4		
	D_6				F_5		

*The following covered the listed areas: Craw (1985)—Aspiring; Bishop *et al.* (1976)—Caples; Norris & Cooper (1977)—Hawea; Turnbull (1981)—Cromwell; Cooper (1974)—Haast; Brown (1968)—East Otago; Findlay (1987)—Copland.

CORRELATION WITH PREVIOUS STRUCTURAL STUDIES

Six penetrative foliation-forming events are recognized in the Otago schists, based on microstructural study. S_1, S_3 and S_5 formed with steep dips; and S_2, S_4 and S_6 formed with gentle dips. At least two semi-ductile fold generations, F_7 and F_8, followed these penetrative deformations. Most of the porphyroblastic rocks used in this study were collected within the Aspiring Terrane in northwest Otago, which was mapped by Craw (1981, 1985).

Craw recognized five phases (D_1–D_5) of deformation in the Aspiring Terrane (Table 1). D_1–D_3 were considered syn-metamorphic, followed by post-metamorphic, non-pervasive D_4 and D_5. D_5 was characterized by conjugate concentric crenulations and broad warps of the main pervasive foliation. The F_5 folds were generally found in phyllosilicate-rich layers only, and correlate with late crenulations observed in this study that have the same characteristics. These structures were only locally developed, and no measurements were made of their orientation though they were always observed to be upright with shallow axes, as shown by Craw (1985, fig. 17). Craw's D_4 correlates directly with the F_7 kink-folds of this study.

Craw correlated his D_3 nappe-forming phase with late nappe-forming phases throughout Otago (Table 1). These D_3 structures have been gently folded by broad D_4 folds, and were generally flat-lying prior to D_4. They correlate with S_6 of this study, which was the last pervasive foliation observed at both the micro and meso scales.

Assuming Craw's overprinting relationships were correctly determined, his D_1 and D_2 structures may be directly, though not uniquely, correlatable with S_4 and S_5, respectively, of this study. Craw's D_1 and D_2 structures are both flat-lying, and associated fold axes were assumed by Craw to be parallel to the F_3 fold axes (though D_1 fold axes are indeterminable). If the correlation between Craw's D_2 and S_5 of this study is correct, then Craw's S_2 would have originally been steeply-dipping, having been rotated to a flat-lying orientation by the effects of D_3.

Findlay (1987) argued that his D_3 structures in the Copland and Cook River Valleys in the south-central Alpine schists were directly correlateable with F_3 structures in the Haast area, and therefore the D_4 structures of Craw (Table 1). The D_3 deformation in the Copland–Cook River area was markedly heterogeneous, with zones of intensely developed, steeply-dipping S_3 (Paringa domains) anastomosing around variably-sized, less deformed pods (Landsborough domains) containing D_3 and older structures. In these pod-like areas of less-intense D_3 deformation, there are apparently large areas of flat-lying S_2 that have been folded to varying degrees around steep F_3 axial surfaces (fig. 14 in Findlay 1987).

If the above correlations are correct, then D_2 and D_3 in the Copland–Cook River area correlates with S_6 and F_7, respectively, of this study. Findlay (1987) argued that D_3 is progressively more intensely developed as the Alpine Fault is approached, where its effects dominate the outcrop. However, this was not observed in the Haast Pass area during this study.

Findlay argued that this structural generation post-dated the Rangitata orogeny, and was associated with shortening against the Alpine Fault. He suggested that the difference in development of D_3 between the Haast area and the Copland area may be because the Alpine Fault dips more steeply in the Copland area (see Allis 1981), causing tighter folding and steeply-dipping zones of high strain (Paringa domains) as a result of shortening against the fault.

MACROSTRUCTURAL ANALYSIS AND REGIONAL TRENDS

Figures 9(a) & (b) are maps of the most prominent foliations and lineations, respectively, in the Otago schists. These foliations and lineations are generally not correlatable from location to location, but several regional trends and relationships are immediately apparent, and where appropriate, will be discussed in more detail later.

(1) The prominent foliation–bedding surface throughout most of the central and southeast parts of the belt is gently dipping, steepening locally as the margins

are approached, where it is generally subparallel to the margins. This has been recognized since the turn of the century (see Wood 1963), and has since been incorporated into several structural interpretations (e.g. Wood 1963, 1978).

(2) Where the prominent foliation surface has a moderate to steep dip, its strike is commonly subparallel to the overall trend of the schist belt, except where the steep dip is caused by young faults oblique to this overall trend.

(3) Textural and lithologic contacts, and metamorphic isograds bordering the southwest side of the belt are parallel to the Livingstone Fault for most of its length, but are progressively truncated by the fault at its northern end (Wood 1962, Mutch & McKellar 1964). The Livingstone Fault is in turn cut by the Alpine Fault, which also truncates textural zones and metamorphic isograds (Mutch & McKellar 1964). This indicates post-metamorphic activity of these faults, and suggests significantly more displacement at the northern end of the Livingstone Fault, relative to the southern and central parts, possibly in conjunction with movement along the Alpine Fault.

(4) Foliations become parallel to the Livingstone Fault where it truncates textural and lithologic contacts, and to the Alpine Fault where it cuts the Livingstone Fault, suggesting relatively ductile deformation associated with movement along these faults.

(5) There are several domains within which lineation orientations are consistent. In the southeast part of the schist belt, the dominant trend is NNW–SSE. In the central schists there are three main orientation domains: N–S, NE–SW and E–W. In the northern schists the lineations are generally NE–SW, subparallel to the Alpine Fault at many locations.

APPLICATION OF AN OROGENIC MODEL

Introduction

The deformation history preserved in the Otago schists, based on my interpretations of micro- and meso-structural relationships, indicates cyclic formation of steeply and gently dipping foliations. As discussed by Bell & Johnson (1989), the preservation of alternating steeply and gently dipping foliations in orogenic belts may indicate alternating cycles of horizontal and vertical shortening during orogenesis.

Bell & Johnson (1989) proposed an orogenic model that involves a repeated two-stage cycle (figs. 24 & 25 in Bell & Johnson 1989). The first stage involves crustal–lithospheric shortening and thickening associated with the formation of a steep foliation. It is followed by the second stage involving gravitational collapse and thinning of the crust–lithosphere associated with the development of a gently dipping foliation. During the first stage, folds form about the steep axial plane foliation, and macroscopic fold vergence changes at the uplift core of the orogen. When uplift reaches a critical level, gravitational forces exceed rock strength and the uplifted pile collapses upon itself. During the collapse stage, gravity sliding and gliding occur at shallow crustal levels, whereas gravity spreading occurs at deeper levels.

Testing the applicability of the Bell & Johnson (1989) *model*

The applicability of the Bell & Johnson model to the Otago schists can be tested by comparing the geometries observed in the schist belt with those predicted by the model. The Bell & Johnson model was designed to accommodate alternately overprinting steeply and gently dipping foliations, and is therefore consistent with these observations from the Otago schists.

The model predicts that an orogen will have some degree of structural symmetry. Such structural symmetry is present in many orogens (see Bell & Johnson 1989), even where geometric symmetry has not been suggested in published cross-sections. In the Otago schists, the asymmetry relationships of overprinting steep S_i shown in Fig. 6, from the localities shown in Fig. 2, consistently indicate a central orogenic core, across which the asymmetry of steep S_i changes (Fig. 10). This suggests that the schist belt has a degree of structural symmetry. This orogenic core corresponds with the core of the Aspiring Terrane in a recently published geological map of northwest Otago (Fig. 10) (fig. 2 in Norris & Craw 1987), and with locations of concentrically zoned ultramafic pods (Cooper 1976). It also corresponds with the metamorphic core of the schist belt, as indicated by localities containing biotite (fig. 5 in Means 1963) and almandine-rich garnet (Brown 1963).

The model predicts the occurrence of thrusts on either side of the orogenic core that displace material outwards from the core, with the development of one or more major detachment surfaces. The Otago schists are bounded on the south and southwest by the Caples Terrane, the Dun Mountain Ophiolite and Livingstone Terrane, and the Maitai Terrane and the Murihiku Terrane. The contacts between most of these terranes dip to the east and northeast, are probably tectonic (e.g. Coombs *et al.* 1976) and are here interpreted as marking the locations of thrust faults.

Major faults have been mapped on the east–northeast side of the schist belt that parallel the belt (Mutch, 1963, Gair, 1967). In many cases these faults are very steeply dipping to vertical, commonly change their dip direction along strike and have associated offsets characteristic of both normal and reverse faults (Bishop 1974, Yeats 1987). It is unclear whether or not any of these faults could have been SW-dipping thrust faults during the Rangitata Orogeny.

Bishop (1974) argued that some of the faults in the Dansey Pass area were major, NE-dipping normal faults in the Cretaceous, with large, vertical displacements up to 5 km. The fact that their orientations closely follow the curvature of the schist boundary strongly suggests a genetic link between these faults and the development of

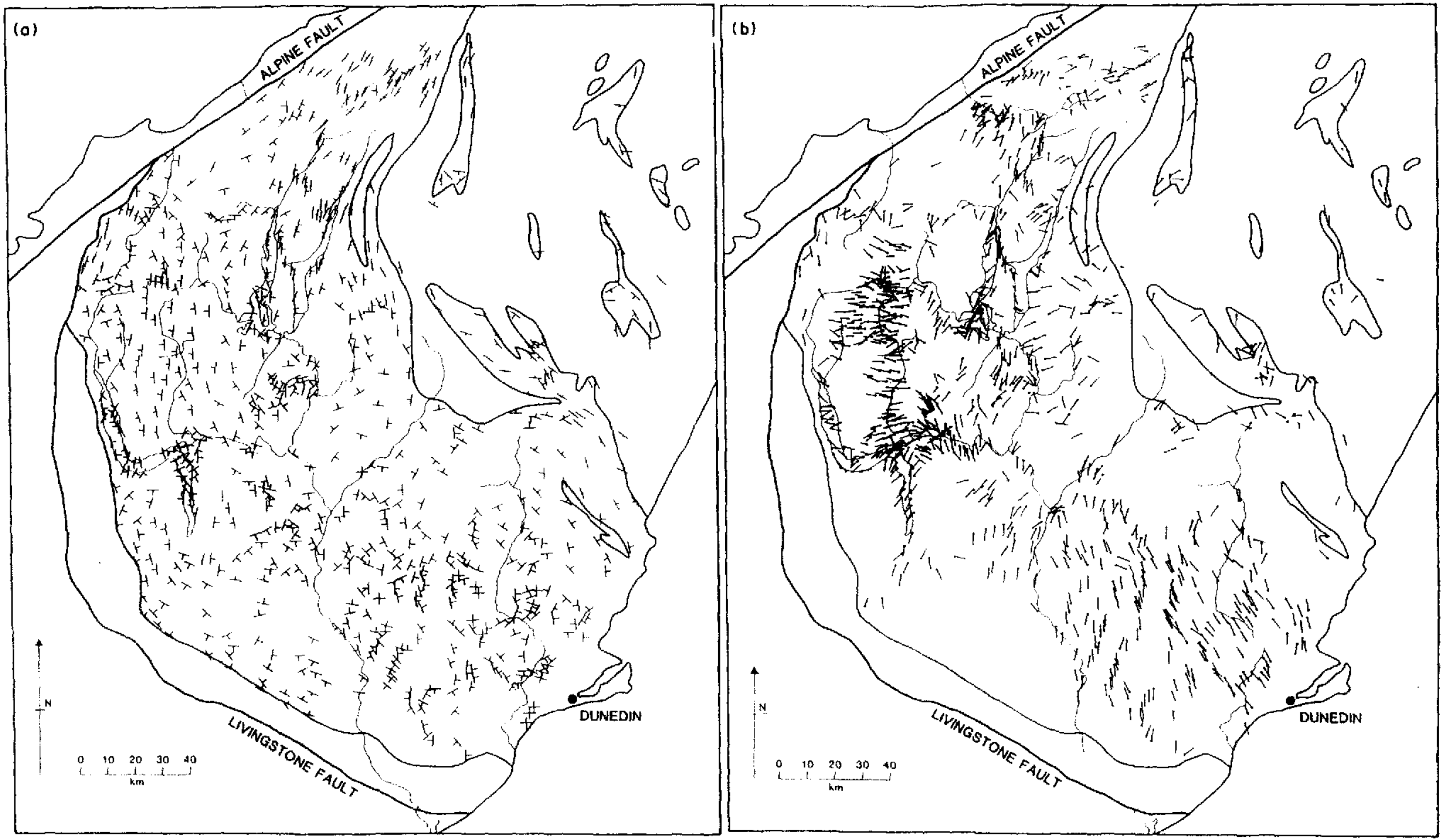

Fig. 9. (a) Detail of area outlined in Fig. 1 showing the strike and dip of main foliation at many locations. See Fig. 2 for details of geology. Length of dip line proportional to dip; steeper dips are shorter in length. Crosses indicate horizontal foliation. Sources of data besides the present author: Wood 1962, 1966, Mutch 1963, Mutch & McKellar 1964, McKellar, 1966, Gair, 1967. (b) Detail of area outlined in Fig. 1 showing the trend and plunge of main lineation at many locations. See Fig. 2 for details of geology. Length of lineation line proportional to plunge; steeper plunges are shorter in length. Sources of data besides the present author: Wood 1962, 1966, Mutch 1963, Mutch & McKellar 1964, Barry 1966, McKellar 1966, Gair 1967, Cooper 1970, Craw 1981.

the schist belt. Their locations and offsets are consistent with them acting to extend the orogen during collapse stages of orogenesis.

The model predicts that in a collapse stage, gently dipping foliations will develop, and extensional high-strain zones associated with gravity spreading will occur on either side of the orogen core, with a top-to-the-core sense of displacement (Fig. 11). These predicted structures are mappable in NW Otago where the Aspiring Terrane is in contact with the surrounding schists (Fig. 10), and were interpreted by Norris & Craw (1987) as thrusts. The same structures are probably present in SE Otago and outboard of the Aspiring Terrane contacts, but the lack of rock-type variation in the majority of the Otago schists makes it difficult to detect them.

The model predicts that the axes of folds forming *early* during both the uplift and the collapse stages should generally be subparallel to one another and oriented subparallel to the length of the belt. This prediction has been confirmed in porphyroblasts (Fig. 7 and associated discussion), where the orientations of these structures are preserved relatively early during their formation. Upright folds formed during an uplift stage will be refolded about gently dipping axial planes during the following collapse stage (figs 24 and 25 in Bell & Johnson 1989). The axes of these recumbent folds should initially be parallel to the length of the belt, but as deformation progresses they will be differentially rotated into the stretching direction associated with gravity spreading (see vergence boundaries, fig. 20 in Wood 1963, and discussion of these boundaries in Wood 1978, fold axes, fig. 1 in Turnbull 1981, nappe rotation in Craw 1985).

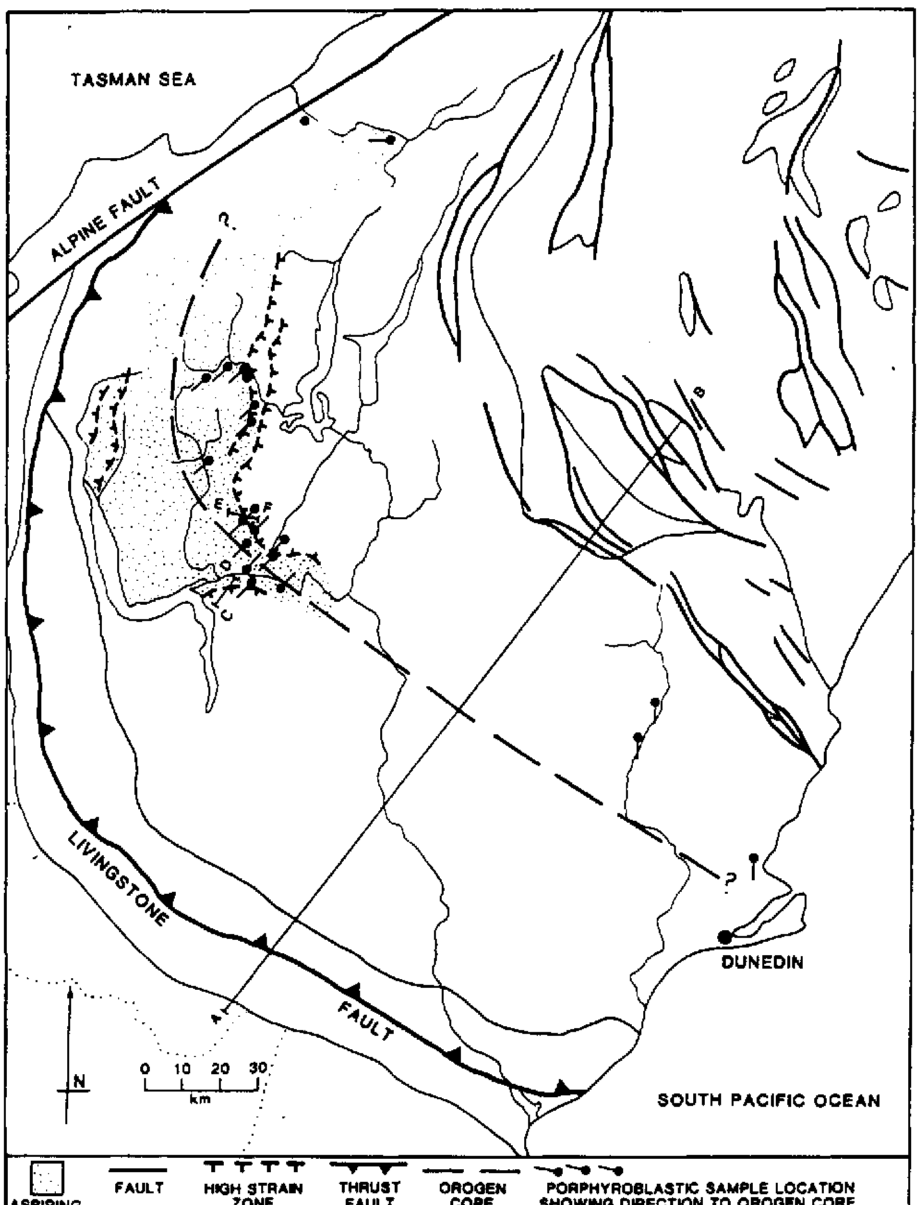

Fig. 10. Detail of area shown in Fig. 1 showing specific structural features predicted by the Bell & Johnson (1989) model of orogenesis. See Fig. 2 for details of geology and porphyroblastic sample location numbers. See text for discussion. Location of Aspiring Terrane rocks and high strain zones from Norris & Craw (1987).

The model predicts that stretching lineations should form at a high angle to the belt during a collapse stage, and down dip during an uplift stage. At the macro scale, lineations in the schists are variable, and the nature and origin of those shown in Fig. 9(b) are largely uncertain, having been measured by several different workers over past years. Assuming these lineations are, for the most part, stretching lineations, a simplistic analysis of their orientations can be made. Any serious analysis would require knowledge of the nature and origin of the lineations, and an attempt to restore them to their orientations prior to any post-Rangitata folding.

Though there are numerous complications and heterogeneities, the overall pattern of lineations from the east coast to the central part of the Aspiring Terrane is roughly fan-shaped (Figs. 9b and 10), with most oriented at a moderate to high angle to the local boundaries of the schist belt. In the eastern part of the belt, lineations are dominantly N- and NW-oriented. Towards the Aspiring Terrane, they progressively swing around to an E–W orientation. This lineation fan may be related to the movement direction during gravitational collapse, and would therefore be consistent with a collapse stage of the Bell & Johnson (1989) model. Immediately north of the main occurrence of the Aspiring terrane, lineations swing into N and NE orientations, presumably due to deformation associated with the Alpine Fault.

At the micro scale, lineations (stretching lineations, Fig. 7) observed on shallow S_i in horizontal thin sections lie generally at a high angle to the strike of steep S_i, and therefore the length of the belt. Many vertical thin sections were cut parallel to the strike of steep S_i in several samples in an attempt to identify stretching lineations on these S_i. As with shallow S_i in horizontal thin sections, S_i in these thin sections were rarely well developed. Where inclusions were observed, they were generally steep, or down-dip, as predicted by the model.

If the stretching direction is down-dip during an uplift stage, upright folds formed during this stage may have their axes rotated into the down-dip stretching direction where the deformation was intense. This may explain the occurrence of steeply plunging, reclining folds in the Wanaka–Hawea area, the axial plunges of which change along trend such that they resemble "canoe prow shapes" (Wood 1978).

Tracking rock paths through the orogen

Rock paths can potentially be determined using the asymmetries of overprinting S_i in porphyroblasts. In the Bell & Johnson model, asymmetries associated with the long limbs of folds will occur more commonly than those associated with the short limbs of folds, because long limbs are expected to dominate any sufficiently large volume of rock during folding. When long-limb asymmetries are considered, the Bell & Johnson model can be divided into four general asymmetry quadrants (Fig. 12). During any orogenic uplift stage, long-limb asymmetries in the two left quadrants will indicate a sinistral sense of displacement, with a dextral sense for the two right side quadrants (Fig. 12a). During any collapse stage, long-limb asymmetries in the upper-left and lower-right quadrants will have a dextral sense of displacement, and vice versa for the upper-right and lower-left quadrants (Fig. 12b).

Porphyroblast S_i asymmetries should generally reflect the quadrant in which a particular S_i was preserved. For example, the path of the porphyroblast shown in Fig. 5(a), provided it represents the dominant long-limb asymmetries for that part of the belt, can be tracked as follows. It has an early steep S_3, followed by gently dipping S_4 and then steep S_5, both with sinistral asymmtry, followed finally by S_6 with dextral asymmetry. Using the asymmetry of S_5, the porphyroblast is assumed to lie to the southwest of the active uplift core (the photomicrograph is taken looking northwest). S_4 and S_6 have opposite asymmetries, which can be interpreted as meaning that, during the uplift stage when S_5 formed, the porphyroblast crossed from the lower-left quadrant,

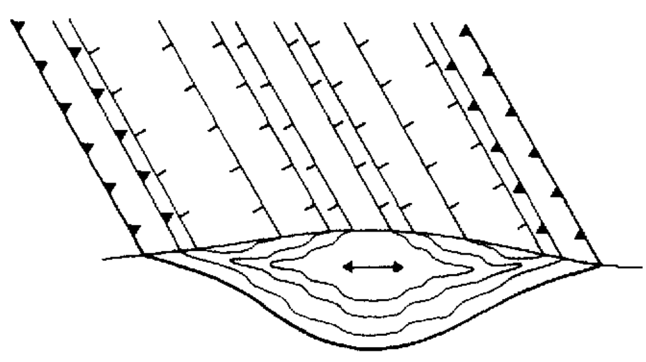

Fig. 11. Three-dimensional sketch showing cross-section of an orogen during a collapse stage, after significant erosion, and the surface expression of extensional high-strain zones (ticks) and thrust faults (barbs). The extensional high-strain zones are located along the long limbs of recumbent, nappe-like folds that were actively accommodating shearing strain during the collapse stage.

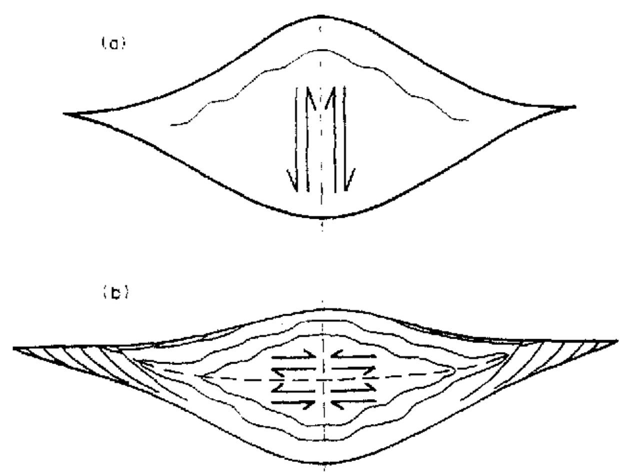

Fig. 12. (a) Schematic diagram showing the bulk sense of displacement expected during an uplift stage of orogenesis. (b) Schematic diagram showing the bulk sense of displacement expected during a collapse stage of orogenesis.

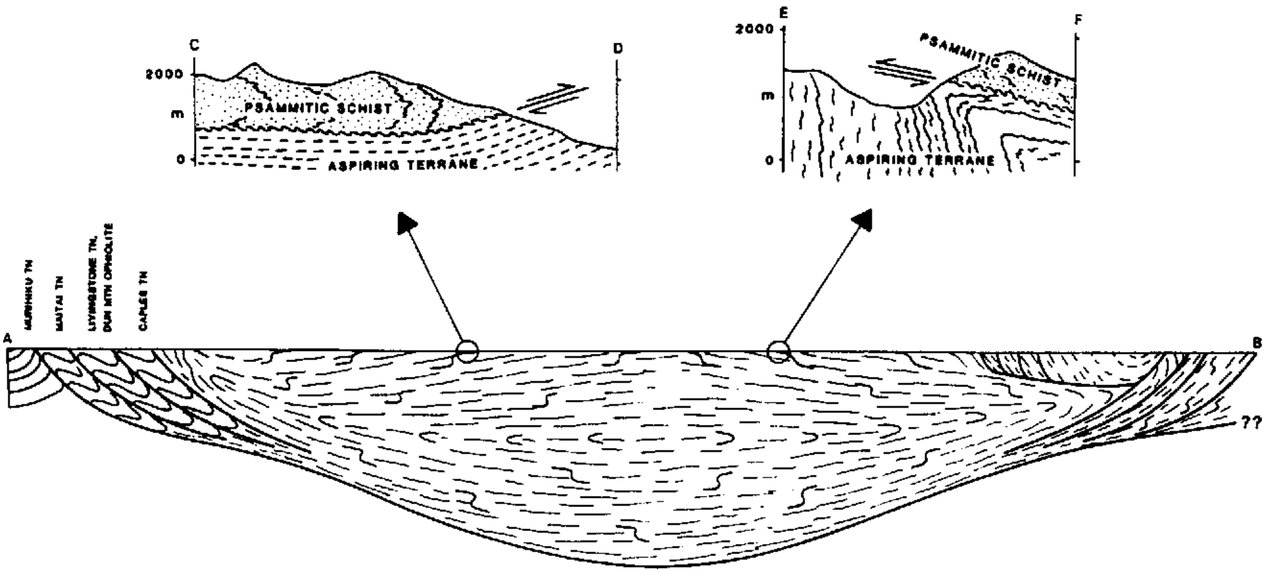

Fig. 13. Cross-sections along lines A–B, C–D and E–F in Fig. 10. Section A–B is based on data from this study, Mutch (1963) and Wood (1966). Sections C–D and E–F are modified after Norris & Craw (1987).

where S_4 formed, to the upper-left quadrant, where S_6 formed (cf. Fig. 12).

Thus, the porphyroblast can be interpreted as migrating upward through the left, or southwest, side of the orogen with time. The sense of displacement associated with the last stage of porphyroblast inclusion trails (S_6) is correlatable with movement along the major high-strain zones that bound the Aspiring Terrane (cf. Figs. 5a, 10 and 13).

In orogens where detailed P–T information can be obtained, detailed P–T–t deformation paths could be determined. Because of the complex interaction of thrusting, spreading and folding during such a progressive orogeny, these paths are expected to be complex, commonly discontinuous, and partially dependent on starting position within the orogen.

Discussion

An orogenic belt is a complex system formed by a large number of hierarchical processes, many of which are poorly understood. No orogenic model can, therefore, be expected to completely account for all of the processes and geometrical complexities. However, from the above discussions it appears that, geometrically and kinematically, the orogenic model proposed by Bell & Johnson (1989) successfully accounts for the observed micro-, meso- and macroscopic geometries and geological relationships in the Otago schists.

This is not the only model that can accommodate both compression and extension; for example, those based on critical shape theory can as well (e.g. Platt 1986, 1987, Jamieson & Beaumont 1988). However, the Bell & Johnson model provides more detailed predictions about specific geometric, kinematic and geological relationships.

The model can be described using critical shape theory, but this description would require two wedges of variable relative size, depending on the degree of structural symmetry of the orogen, rather than one backed by a rigid buttress (S. E. Johnson unpublished data). Single-wedge models backed by a rigid buttress are not compatible with the large degree of structural symmetry commonly found in orogens, regardless of the scale at which that symmetry is observed (see Bell & Johnson 1989). Using critical shape theory would also require the limiting assumption that the orogen has a bulk rheology.

In terms of the Bell & Johnson model, the Otago schists appear to preserve a collapse stage of orogenic development. Figure 13 is a highly generalized, interpretive cross-section through the Otago schists (Fig. 10), during the Rangitata Orogeny, showing what the orogen may have looked like during a collapse stage.

The lower boundary of the diagram is a basal detachment surface, below which is crust (not shown) that is not involved in deformation during the collapse stage (Bell & Johnson 1989). Strain taken up along this detachment at depth is distributed into several thrusts as the orogen margins are approached. Note that the extent of this basal detachment to the North is unclear, and that it could potentially penetrate well into the Torlesse Terrane (Figs. 2 and 10). Individual terranes do not necessarily extend to the depths shown on this diagram, nor are they expected to retain the distinct characteristics used to define them at the surface.

Two groups of faults are shown at the northern end of the cross-section. The first are the NE-dipping, high-angle normal faults mapped by Bishop (1974) in the Dansey Pass area. These normal faults are interpreted as a zone of gravity sliding or gliding above a zone of gravity spreading, and may or may not sole onto a detachment at depth, as shown in the cross-section.

The second group of faults are SW-dipping thrust faults. These thrust faults are not documented in the published literature, and, if they exist, as predicted by the model, they may be completely overlain by zones of gravity sliding and gliding.

The detailed sections C–D and E–F (Fig. 10) shown in Fig. 13 are modified from Norris & Craw (1987), who interpreted them as thrusts, and illustrate extensional high-strain zones shown in Figs. 10 and 11. These sections are projected onto section A–B to illustrate their positions relative to the orogen core.

During a collapse stage these extensional high-strain zones should be flat-lying near the core, but they may be bent up near the thrusts on the lateral extremes of the orogen (Figs. 11 and 13), where they may be mistaken as thrust faults. During an uplift stage, or, in the case of the Otago schists, during post-Rangitata folding, these zones will be folded into various orientations (e.g. Norris & Craw 1987).

RANGITATA RECONSTRUCTION, AND EFFECTS OF LATE-CENOZOIC DEFORMATION AND ASSOCIATED ALPINE FAULT MOVEMENT ON THE OTAGO SCHISTS

Figure 14 shows a proposed reconstruction of New Zealand basement terranes, including the Haast Schist Terrane, during the early Tertiary (modified from Bradshaw *et al.* 1980 and Kamp 1987). Much of the arcuate

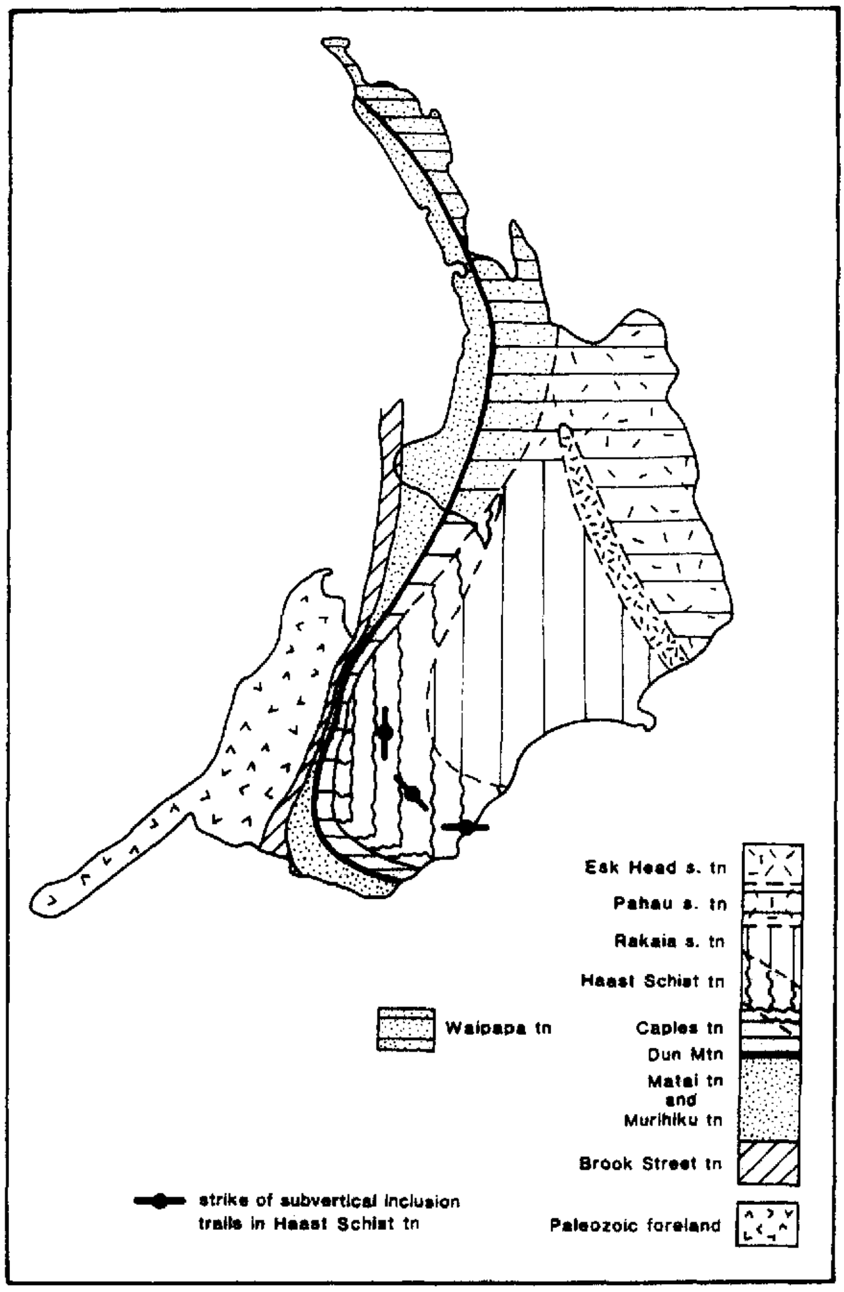

Fig. 14. Late Cretaceous–early Tertiary reconstruction of Permian–Jurassic terranes of the Rangitata Orogeny. The shape of the Haast Schist Terrane is based on the strike of steep S_i in porphyroblasts. Modified from Bradshaw *et al.* (1980) and Kamp (1987).

shape of basement terranes in the southern South Island, therefore, may have formed prior to the early Tertiary, possibly as a result of late Triassic subduction collision of a wedge-shaped Rakaia subterrane with the pre-existing arc to trench assemblage of the Brook Street through Caples Terranes (e.g. Coombs *et al.* 1976, Kamp 1987). As discussed by Kamp (1987), the coincidence of the distribution of the Rakaia and Haast Schist Terranes with the portion of the arc that is concave to the east, strongly suggests a genetic link between accretion of the Rakaia subterrane, formation of the schist belt and formation of the arc. This arc must have significantly tightened in the Cenozoic, as a result of Alpine Fault-related deformation (e.g. Norris 1979, Walcott 1979, Norris & Carter 1982).

The average strikes of steep S_i in the NW, central and SE domains (cf. Fig. 8) shown on Fig. 14 are compatible with the shape of the Haast Schist Terrane in the reconstruction. Because most of the S_i and S_e measured to generate Fig. 8 were the late S_5 foliation (e.g. Fig. 3a), it appears that the arc existed at the time S_5 formed. The strike of earlier steep S_i (S_3 and possibly S_1) could only be determined in the central domain, where they had the same strike in horizontal thin sections (see Fig. 7b). The central domain is therefore interpreted to have had approximately the same trend throughout much of the Rangitata orogeny. This may have occurred because the central domain lay at the apex of the arc (Fig. 14).

In the Otago schists, the effects of post-Rangitata deformation are largely reflected by the imprint of generally NE structural trends upon N–S trends formed during the Rangitata Orogeny. The effects range from negligible deformation in the far southeast, to steep folding and major uplift and faulting in the Alpine schists, associated with Alpine Fault movement (e.g. Cooper 1974, Findlay 1987).

As discussed earlier, F_7 of this study, which is correlated with F_4 of Craw (1985), F_3 of Cooper (1974) and F_3 of Findlay (1987) (see Table 1), appears to be a late Cenozoic, Alpine Fault-related structure. F_3 of Cooper (1984) has recently been dated as late Oligocene–early Miocene (Cooper *et al.* 1987) using lamprophyre dikes, by arguing that F_3 folds and the dated dikes formed simultaneously during wrenching related to the inception of the Alpine Fault. Craw (1985) and Findlay (1987) argued for a mid-Tertiary age for their structures, and Findlay suggested they were related to shortening deformation along the Alpine Fault.

CONCLUSIONS

(1) The development of up to six penetrative foliations in the Otago schists was determined from detailed microstructural analysis. S_1 and S_2 were found only as inclusion trails in porphyroblasts. S_1, S_3 and S_5 formed with steep dips, and S_2, S_4 and S_6 formed with gentle dips. At the apex of the arcuate shape outlined by basement terranes in the South Island, fold axes associated with S_1–S_6, at the time of porphyroblast growth, were probably subparallel to one another, striking NW and gently plunging.

(2) Development of these six penetrative foliations was followed by two folding events (F_7, F_8) that, in the Otago schists, were commonly semi-brittle, and are interpreted as post-metamorphic. F_7 structures are correlated with intensely developed structures in the southern and south-central Alpine schists. These structures are considered to have formed during late Cenozoic, Alpine Fault-related deformation.

(3) Observed structural and geological relationships at all scales within the Otago schists are reasonably compatible with the orogenic model proposed by Bell & Johnson (1989). An orogenic uplift core predicted by the model is defined by the asymmetry of foliations trapped in porphyroblasts. This core coincides with the Aspiring Terrane in NW Otago, which is most readily interpreted as an oceanic suite of lithologies (e.g. Norris & Craw 1987). The Otago schists appear to be in the collapse stage of the Bell & Johnson (1989) model. This stage is characterized by flat-lying foliations associated with nappe development; high-strain zones along the limbs of nappes, which appear to displace material towards the core from either side of it; and gravity spreading-driven thrusting on at least one margin of the orogen.

(4) The strike of S_5 in porphyroblasts measured from horizontal thin sections is consistent with the arcuate shape of the schist belt in late Cretaceous–early Tertiary, pre-Alpine Fault reconstructions, suggesting that the arcuate shape was well developed by the time of porphyroblast growth.

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