Journal of Structural Geology, Vol. 11, No. 8, pp. 1029 to 1037, 1989
Printed in Great Britain

0191-8141/89 $03.00+0.00

Plagioclase and quartz preferred orientations in a low-grade schist: the roles of primary growth and plastic deformation

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(*Received* 11 *November* 1988; *accepted in revised form* 8 *May* 1989)

Abstract—Albite in a lower greenschist facies Haast Schist from New Zealand has a maximum of poles to [001] parallel to the elongation direction; [010] forms a girdle about grain length. Plastic deformation with slip dominantly on (010)[001] is rejected as the orienting mechanism because: (1) the relationship of crystal axes to grain length would require multiple slip systems incompatible with the lack of rotation of albite twin planes; (2) euhedral terminations and other textural features indicate primary crystallization; (3) albites in quartzose layers are less elongate than those in sheet silicate-rich layers. The albite fabric is ascribed to growth anisotropy and competition in response to stress-driven solution and growth during formation of metamorphic segregation layering. This explanation is compatible with the common observation that plagioclase is brittle at low metamorphic grades. Associated weak quartz *c*-axis fabrics are ascribed to plastic deformation, and this deformation enhanced a dimensional preferred orientation already established by primary growth.

INTRODUCTION

FELDSPAR is by far the most abundant crustal mineral, yet work on feldspar preferred orientations in deformed rocks lags well behind that on other minerals such as the sheet silicates, quartz and calcite. In the recent book by Wenk (1985) on preferred orientations, feldspar is conspicuous by its absence. The reasons are not difficult to find: universal stage work to determine the feldspar preferred orientation in one specimen may take several days compared to several hours for many other minerals; and because most feldspars are triclinic, there is only a rough correlation to be made between optics and crystal directions. Provided the positions of {010} and {001} can be observed, it is possible, using the optical data, to make a complete determination of the lattice orientation (Wenk *et al.* 1986), and Kruhl (1987a) and Benn & Mainprice (in press) have described computer-assisted methods to speed such determinations. There seems to be no satisfactory X-ray method, and the only alternative suggested is the expensive and, for many, inaccessible neutron diffraction analysis recently described by Wenk *et al.* (1986).

Despite the difficulties, several workers have described feldspar fabrics in the last 5 years, including Olsen & Kohlstedt (1985), Kruhl (1987b,c), Shaocheng & Mainprice (1988) and Shaocheng *et al.* (1988). The thrust of these papers is that feldspars have undergone plastic deformation to produce a crystallographic preferred orientation. Plastic deformation is thought to be effective only at temperatures in the amphibolite facies (possibly upper greenschist facies), or higher. Transmission electron microscopic studies (Olsen & Kohlstedt 1985, Montardi & Mainprice 1987), experimental work (Borg & Heard 1970, Marshall & McLaren 1977) and optical studies, have documented various slip mechanisms, especially (010)[001] slip. At low grades of metamorphism, feldspars behave dominantly in a brittle manner, and this is shown by the difficulty of experimental plastic deformation at low temperatures (Tullis & Yund 1987), and the common observation in naturally deformed rocks that ductile minerals such as quartz and sheet silicates are bent and deformed around broken feldspar porphyroclasts (Boullier 1980).

In this paper I describe an albite preferred orientation and associated quartz and sheet silicate fabrics from a lower greenschist facies chlorite-schist from New Zealand. I show that the textures and fabric are incompatible with intracrystalline slip, and propose instead an origin by growth anisotropy involving competition between grains.

LOCATION OF THE SPECIMEN

The Haast Schist crops out as a broad 100 km wide belt running SE–NW from Dunedin across the southern half of the South Island of New Zealand (Fig. 1). The belt changes orientation at its NW end so as to form a narrower outcrop 10–40 km wide running NE–SW along the length of the Alpine Fault. Lower greenschist facies rocks make up most of the outcrop, with higher grade schists found only near the Alpine Fault. The specimen described here (DS970) comes from an area of greenschist facies metamorphism at the boundary of the chlorite and biotite zones. It was collected from a roadside exposure alongside the Haast River (1 : 63,360 topographic map, NZMS 1, sheet S87, Haast, grid reference 175008), and the exact location and the positions of zone boundaries (after Cooper 1971) are given on the map in Shelley (1973).

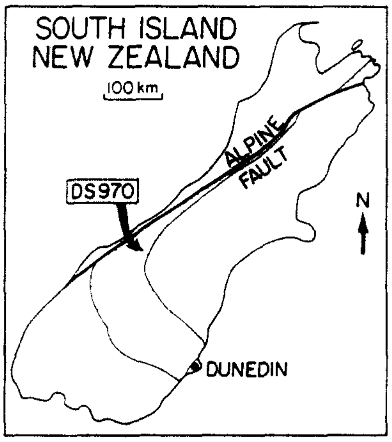

Fig. 1. Map to show distribution of Haast Schists (stippled) in New Zealand and location of specimen DS970.

GENERAL TEXTURAL FEATURES OF DS970

The rock is a typical Haast Schist, containing albite (30%), quartz (30%), muscovite (20%), chlorite (15%), biotite + opaques + others (5%). The schist is layered so that *ca* 5 mm thick quartz–albite layers alternate with *ca* 2 mm thick layers rich in sheet silicates. Layering of metamorphic origin is usually already well-developed in the Haast Schists within the chlorite zone (Turner 1935, Hutton & Turner 1936, Bishop 1972). There is a macroscopically visible lineation, and in sections parallel to the lineation, perpendicular to layering, the layering appears continuous. This contrasts with its generally discontinuous appearance in sections perpendicular to the lineation.

In sections parallel to the lineation, albite grains are elongate parallel to the lineation and layering (Figs. 2a and 3a). Grains are generally less than 0.7 mm in length. Albite is irregularly distributed in the quartzose layers: in quartz dominant areas, isolated albite grains may seem to be completely surrounded by quartz (Fig. 2a); more generally, albite is found as clusters of elongate grains, and the re-entrant angles between albite grains are often occupied by quartz (Fig. 2a). In sections perpendicular to the lineation, albite grains in the quartzose layers have an equidimensional aspect (Figs. 2b and 3b). Again, most grains form a connected network with re-entrants occupied by quartz. In three dimensions, therefore, the albite forms an interconnecting mass of elongate polyhedra each having the general shape of a prolate spheroid, and with the ends of grains often surrounded by quartz. The grain length defines the lineation of the schist.

In the sheet silicate-rich layers, albite grains embedded in sheet silicates are common (Fig. 3d); much less common is quartz.

Of particular interest is the common presence of euhedral terminations to albite (Fig. 4). The faceted terminations are most often set within a single quartz grain, but sometimes within another albite (Fig. 4b).

Albite grains with a curved or irregular aspect are common (Figs. 3c & d); they are not usually accompanied by bending of the lattice, a fact confirmed by close examination with the universal stage. In the sheet silicate layers, some albites have an interdigitating relationship with the sheet silicates (Fig. 5a). Of particular significance is the occurrence of simple, occasionally repeated, often stepped, albite twins (Figs. 3c and 4c & d). These are primary growth twins using the criteria of Vance (1961). Twin planes are seldom bent, even in elongate grains with the twin plane at a high angle to the grain length (Fig. 3c), and universal stage observations always confirm the albite twin plane to be in its expected crystallographic position. Repeated twinning which could be ascribed to deformation is rare, as is pericline twinning. Very rare detrital relics characterized by an unusual degree of alteration and clouding do show possible deformation twins.

The quartz accompanying albite in the quartzofeldspathic layers usually forms elongate polyhedra, similar to the albite, and many grains could be described as quartz 'ribbons' (Figs. 3e & f). In contrast to the albite, optically visible strain features are common in quartz, and clearly it has been plastically deformed, developed sub-grains, and possibly new grains. In fact, there is every gradation between ribbons with minor sub-grain development, ribbons where the orientations of adjacent sub-grains have diverged by several degrees, and elongate groups of relatively equidimensional grains which may result from the recrystallization of ribbons.

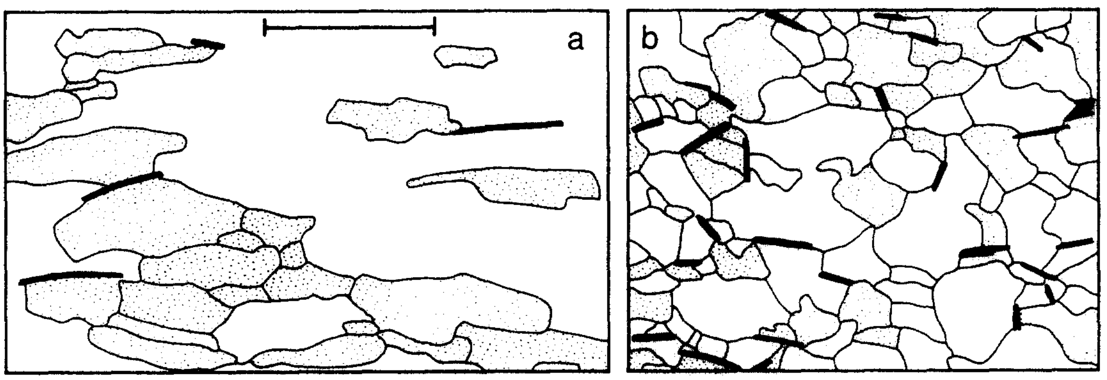

Fig. 2. Albite grains in quartz-rich layers. (a) General view of elongate albite grains in thin section perpendicular to schistosity and parallel to lineation. (b) General view in section perpendicular to lineation. Albite is stippled, sheet silicate grains are shown as thick lines, and quartz is blank (grain boundaries not shown in a). Scale bar 0.3 mm.

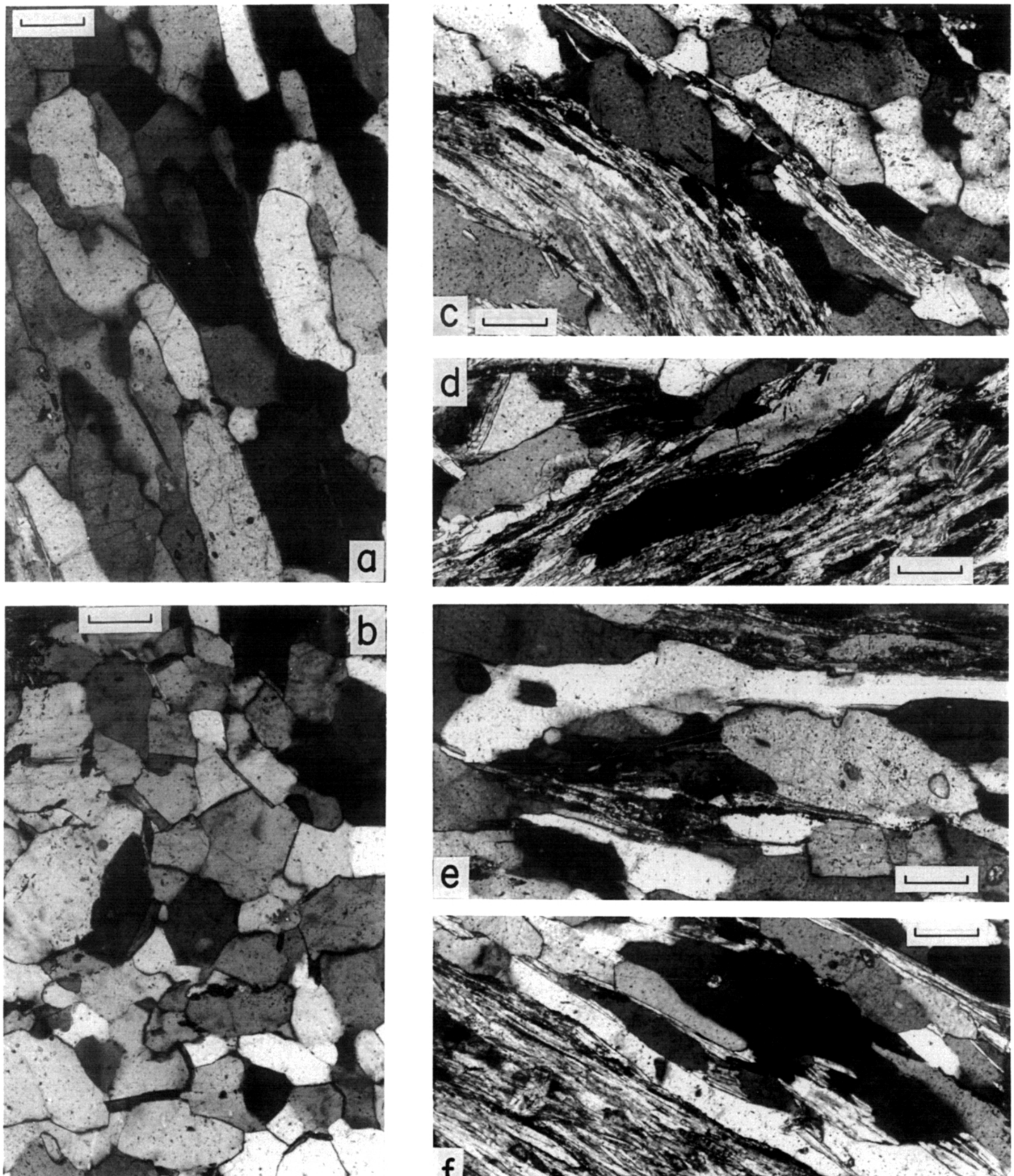

Fig. 3. Photomicrographs in crossed-polarized light. Scale bars 0.1 mm. (a) Elongate albite and quartz grains in section perpendicular to schistosity and parallel to lineation. (b) Typical view in section perpendicular to lineation. (c) Albite in quartzose layer adjacent to sheet silicate-rich layer showing curved form and twin at high angle to grain length (the twin runs *ca* N–S in the centre of the photograph, and the twinned part to the right is in extinction). U-stage observations show that the twin plane is exactly (010), and that the lattice is not bent. (d) Albite grain that seems bent although U-stage observations show this not to be the case. (e) Quartz 'ribbon'. The slight variations in shade correspond to the segmentation of the 'ribbon' into three subgrains. (f) Very elongate quartz 'ribbon' at boundary between quartzose and sheet silicate-rich layers.

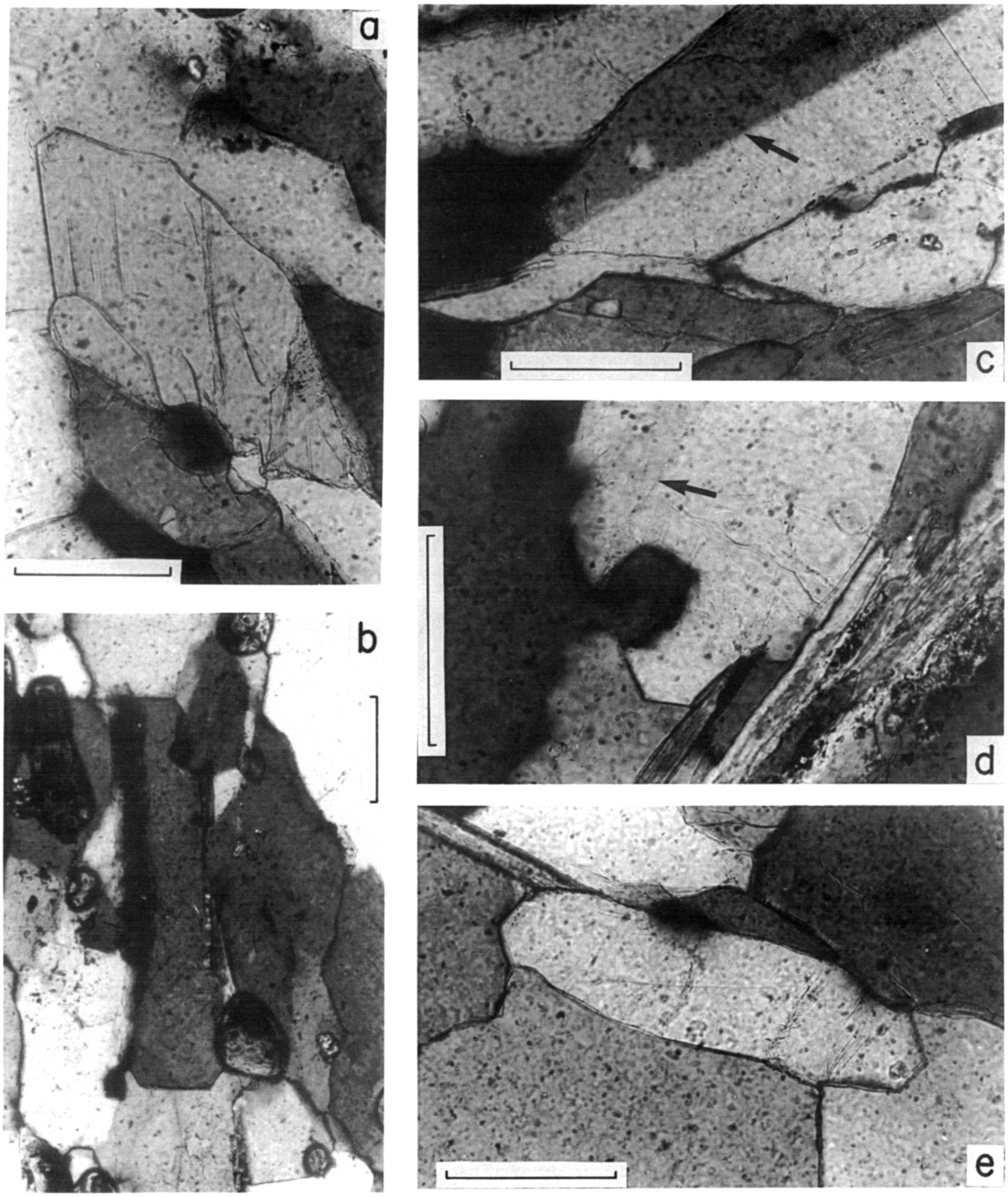

Fig. 4. Photomicrographs in crossed-polarized light showing euhedral terminations to albite grains. Scale bars 0.1 mm. (a) Albite with three crystal faces embedded in quartz at top left. (b) Albite with parallel sets of faces at both ends. Lower end is embedded in another albite grain, the upper end in quartz. (c) & (d) Simple albite twins (arrowed) in grains with euhedral terminations at bottom left. (e) Albite with parallel sets of faces at both ends embedded in quartz.

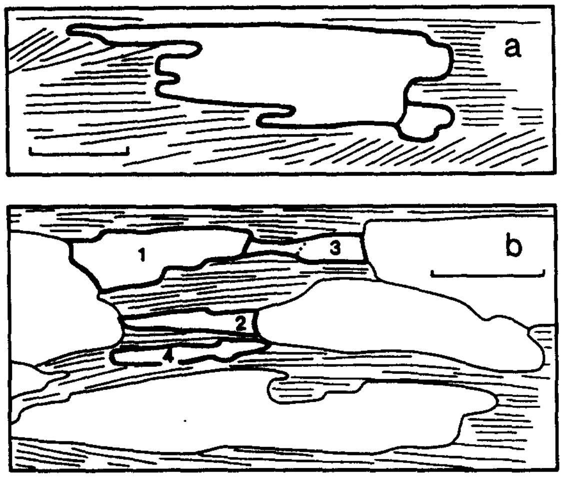

Fig. 5. (a) Albite which interdigitates with sheet silicates in a sheet silicate-rich layer. (b) Elongate quartz grains in sheet silicate-rich layers. Grains 1 and 2 have *c*-axes nearly parallel to schistosity. Grains with bold outline are quartz, other clear grains are albite and closely lined areas represent sheet silicates. Scale bars 0.1 mm.

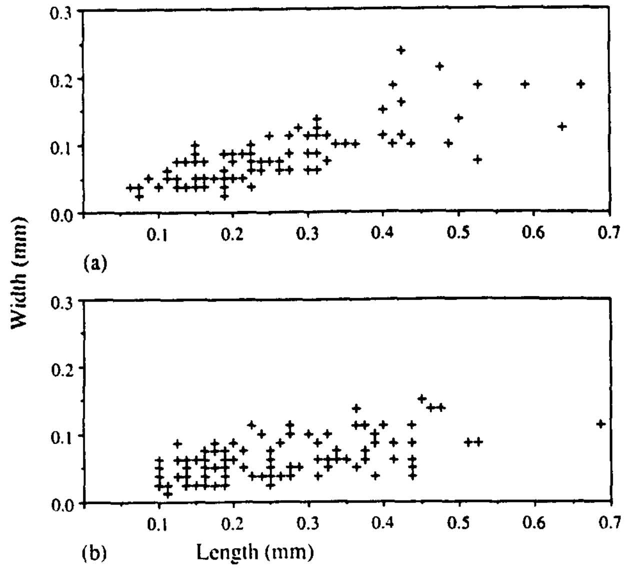

Fig. 7. Data from section cut parallel to lineation, perpendicular to foliation. Albite length plotted against width for (a) quartzose layers, and (b) sheet silicate-rich layers.

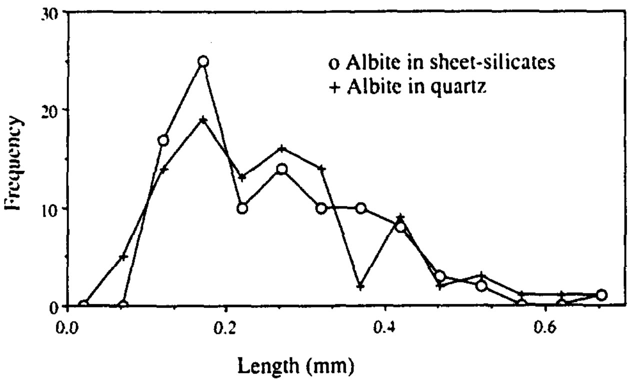

Fig. 8. Data from section cut parallel to lineation, perpendicular to foliation. Frequency diagram for length of albite grains in quartzose and sheet silicate-rich layers.

Some 'ribbons' of quartz have developed in the 'shadow' of feldspars (Fig. 5b), especially in the sheet silicate-rich layers.

Sheet silicates are concentrated in layers, but also form scattered grains throughout the quartzose layers. Cleavage traces of the sheet silicates in the section parallel to the lineation are strongly aligned parallel to the layering. Perpendicular to the lineation, cleavage traces are much more randomly orientated (poles to cleavage form a girdle around the lineation, but with a maximum defining the schistosity of the specimen—Fig. 12b). In general, the sheet silicates in the sheet silicate-rich layers form an interlocking mass of relatively strain-free grains, though minor bending of grains is quite common.

ALBITE GRAIN DIMENSIONS AND THE DIMENSIONAL PREFERRED ORIENTATION

Albite grains are consistently elongate parallel to the lineation and layering, and Figs. 6, 7 and 8 illustrate more precisely the shapes and dimensional orientation of the albite, as measured in a section parallel to lineation, perpendicular to layering.

Albite grains in the quartz–albite layers are generally three times as long as they are wide with ratios up to 7 : 1 (Fig. 6a); albite grains in the sheet silicate layers are longer, generally over four times as long as wide, and with ratios up to 12 : 1 (Fig. 6b). The angle by which the long axes deviate from the overall attitude of layering is greater (up to 15°) in the quartz–albite layers.

There is a positive correlation between length and

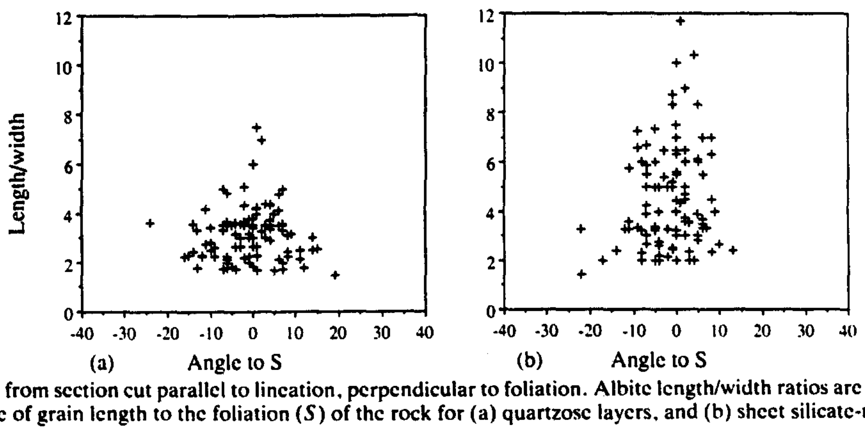

Fig. 6. Data from section cut parallel to lineation, perpendicular to foliation. Albite length/width ratios are plotted against the angle of grain length to the foliation (*S*) of the rock for (a) quartzose layers, and (b) sheet silicate-rich layers.

width of albite grains in both the quartz–albite and sheet silicate layers (Fig. 7), although the increase in width with length is greater in the quartzose layers. In other words, albite grains embedded in sheet silicates tend to be more slender than those embedded in quartz or feldspar, a feature already evident from Fig. 6.

Figure 8 shows the frequencies of the lengths of albite grains for the two types of layer. The maximum length of albite is the same for both layer types, and the overall distributions of length frequency are very similar.

ALBITE CRYSTALLOGRAPHIC PREFERRED ORIENTATION

The complete determination of albite lattice preferred orientation requires the positions of {010} and {001} to be known, as well as the optic directions (Wenk *et al.* 1986). These requirements cannot be met for the majority of the Haast Schist albite grains. For example, many do not display albite twinning or the {010} cleavage, even when suitably oriented to do so, and because of limitations on the degree of rotation possible with the U-stage, it may not be possible to rotate cleavage planes into observable orientations. Furthermore, the fine grain size of the albites often means that no cleavages are developed. In common with previous workers, the option of reporting the optic orientation is adopted here. According to Burri *et al.* (1967), low-temperature albite (An_{0-5}) has optic directions X 20° from [100], Y 16–18° from [001] and Z 14° from [010], to that X, Y and Z closely approximate the positions of [100], [001] and [010], respectively. The optical fabrics of albite described below were measured in a thin section cut perpendicular to schistosity and parallel to lineation. The same fabrics have also been measured in a section perpendicular to lineation.

Universal stage measurements of the optical directions X, Y and Z of 300 grains show a weak but well defined maximum of Y parallel to the lineation (Fig. 9a), a less well defined girdle of Z about the lineation (Fig. 9b), and no preferred orientation of X. In terms of the lattice, [001] is oriented parallel to the lineation, and the pole to (010) or [010] forms a girdle about the lineation. There is no obvious direct connection between grain shape and crystallographic orientation. Thus, grains with Y at a high angle to the lineation have similar length/width ratios to those with Y parallel to the lineation (Fig. 10). Figure 10 represents data for the quartzose layers, but the same general relationship holds in the sheet silicate-rich layers, so that the very elongate albite of Fig. 5(b), for example, has Y at a high angle to schistosity.

The parallelism of feldspar [001] to a lineation is the most common fabric in thoroughly recrystallized and deformed rocks, although the documentation of this fact has been slow (Crampton 1957, Shelley 1977, Olsen & Kohlstedt 1985, Kruhl 1987b,c, Shaocheng & Mainprice 1988). The other common feldspar fabric (the parallelism of [100] and a lineation) is usually caused by the mechanical re-orientation of igneous-shaped grains during strain, sometimes preserved despite thorough recrystallization (Shelley 1979).

In the New Zealand Haast Schists, the [001] parallel to lineation fabric is found at the chlorite–biotite zone boundary (lower greenschist facies—this paper), in the garnet zone (upper greenschist facies) and amphibolite facies (Shelley 1977). Since the Haast Schists are richly

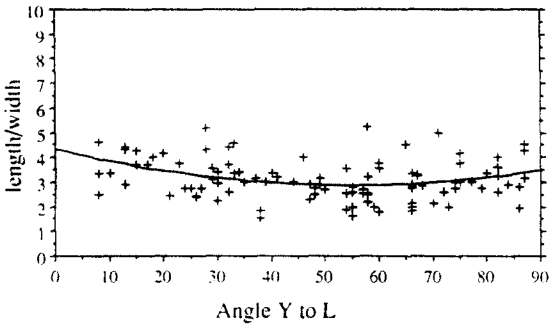

Fig. 10. Data from section cut parallel to lineation, perpendicular to foliation. Albite length/width ratios in quartzose layers are plotted against the angle between the Y optic direction and the lineation. The overall reduction in length/width ratio with increase in angle Y to lineation mainly reflects an overall reduction in lengths.

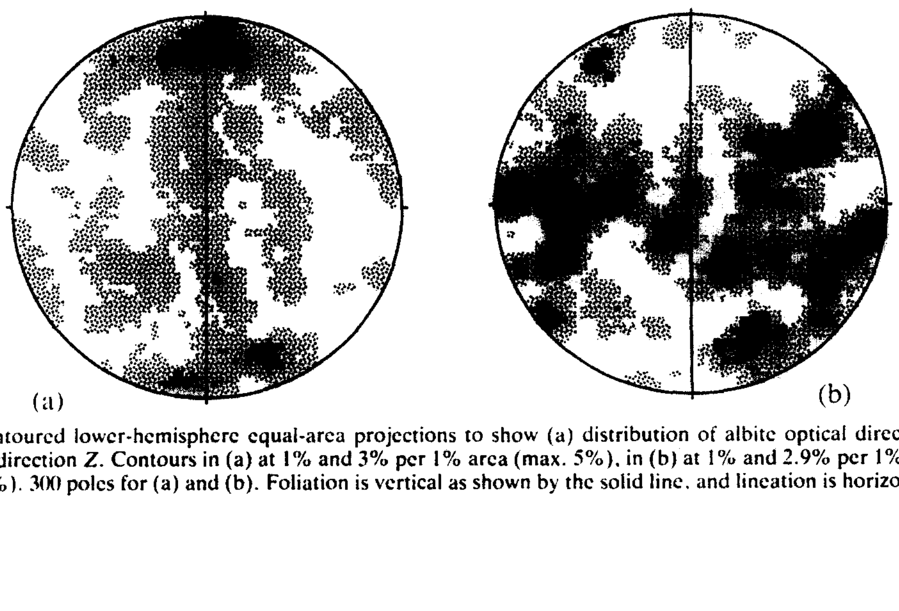

Fig. 9. Contoured lower-hemisphere equal-area projections to show (a) distribution of albite optical direction Y, and (b) optical direction Z. Contours in (a) at 1% and 3% per 1% area (max. 5%), in (b) at 1% and 2.9% per 1% area (max. 3.7%). 300 poles for (a) and (b). Foliation is vertical as shown by the solid line, and lineation is horizontal.

feldspathic, an understanding of feldspar fabrics is vital to any understanding of the overall fabric development of the schists.

INTERPRETATION OF THE FELDSPAR FABRICS

Possible origins of a preferred orientation include plastic deformation, primary growth, the mechanical alignment of elongate grains and the influence of pre-existing fabrics. They are considered in turn below.

Plastic deformation

Grain shapes (Figs. 6, 7 and 8) show a fairly uniform aspect ratio and Y is often at a high angle to elongate grains (Fig. 10). Therefore, although the observed crystallographic preferred orientation would require a dominance of (010)[001] slip, slip systems on planes other than (010) are also required to produce the observed grain elongations. That being the case, albite twin planes would inevitably have been rotated passively out of their true crystallographic positions (Fig. 11). In deformed calcite, for example, such rotations are commonly found where *e* twin lamellae are shifted during later slip on either *r* or *f*. Not only should one expect such rotations, but bending would normally accompany slip except in the most homogeneous of deformations. The lack of rotation and bending of twin planes in Haast Schist albite shows that significant plastic deformation has not occurred.

In addition, the contrasting shapes of albite grains in the two layer types (Fig. 6) seems incompatible with plastic deformation. In the sheet silicate-rich layers one would expect a partitioning of the deformation with sheet silicates wrapped around resistant feldspars. Not only does this not occur, but albites in the sheet silicate-rich layers are thinner than those in the quartzose layers.

The above points show that the occasional observations of slight strain in the albite grains are insufficient to indicate plastic deformation as the orienting mechanism.

Primary growth

The albite grains display many of the characteristics of primary growth, euhedral terminations and primary twins in particular. Although many albites adjoin other albites in a form of mosaic, individual grains are often surrounded by quartz or sheet silicates to a large degree. This is most compatible with primary growth since dynamic or static recrystallization would normally produce an aggregate of grains. The Haast Schists are noted for the development of secondary layering at an early stage of metamorphism (Turner 1935, Hutton & Turner 1936, Bishop 1972). The primary process is one of segregation and growth of minerals at new sites, although dynamic recrystallization and plastic deformation are common secondary processes. Growth mechanisms have been proposed as the cause of preferred orientations of a number of minerals. For example, Ishii (1988) explains sheet silicate fabrics in schist in this way, and Nicolas & Poirier (1976) suggest amphibole fabrics may be dominated by growth. Quartz also demonstrates growth preferred orientations, both dimensional and crystallographic, in quartz veins.

The important factors in producing growth fabrics are the natural growth anisotropy of the mineral and the geometry (and changing geometry) of the growth site. Thus, quartz crystals in a vein nucleate perhaps with random orientations on the vein wall, but the fastest growth direction parallel to *c* ensures that grains with the *c*-axis at a high angle to the wall eliminate other orientations in the competition for space; the result is the commonly observed *c*-axis and long axis perpendicular to the vein wall.

To explain the albite fabrics by primary growth anisotropy requires [001] to be the direction of fastest growth, and the extension direction in the schist parallel to the grain length. Either [100] or [001] are most commonly the fastest growth directions in feldspar (Smith 1974), and the evidence from the Haast Schists is that [001] dominated during metamorphism. The progressive although slight reduction in albite length/width ratios with increase in the angle of Y to the lineation up to 60° (Fig. 10) is a consequence of the anisotropic growth factor. Grains with Y close to the lineation had the advantage, but only to the extent of producing a weak crystal lattice preferred orientation. The grain size data of Fig. 8 show that there are many more small grains than large, and this suggests that competitive growth for space results in the survival of a few larger grains. Because there is a lower grain size limit below which grains cannot be properly observed or measured with the microscope, it can be predicted that measured fabrics will represent the successfully competitive grains. Further investigation is required to determine whether the growth anisotropy factor was most effective in producing the crystal lattice preferred orientation at the late or early (unseen) stages of growth. Further studies relating grain shape and size to lattice preferred orientations promise to be fruitful.

It is not the purpose of this paper to discuss the precise nature and origin of metamorphic layering, but clearly the nature of the mineral fabrics is crucial to such a discussion. A mechanism of layer-parallel growth of quartz–feldspar in greenschist and amphibolite facies rocks has been proposed by Sawyer & Robin (1986), and the stress-driven combination of solution transfer and

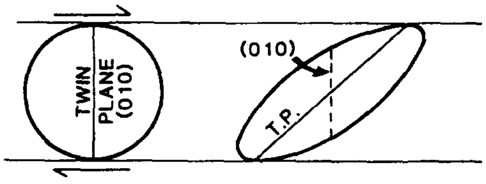

Fig. 11. Diagram to show that slip on a plane at a high angle to (010) will rotate an albite twin plane away from (010), an effect not observed in the Haast Schist.

growth by a kind of crack–seal mechanism within the extending layer seems appropriate in the Haast Schists.

Other mechanisms

The mechanical alignment of inequidimensional grains seems inappropriate as an orienting mechanism for Haast Schist albite, given that the layering represents segregation and growth of material, and that the textural evidence indicates growth *in situ*. Nor is it likely that the orientation of detrital grains had any influence on the orientation of the new albite growth since detrital grains would be elongate parallel to [100] (bound by cleavages), not [001].

ASSOCIATED QUARTZ AND SHEET SILICATE FABRICS

Quartz *c*-axes form a weak girdle about the lineation (Fig. 12a). The maximum does not coincide with the pole to the layering, and the entire quartz *c*-axis fabric is asymmetric with regard to all other measured fabric elements. In contrast to the albite, quartz shows abundant signs of plastic deformation in optical strain effects and sub-grain formation; recrystallization effects are also evident. Therefore, the weak *c*-axis fabric could be explained as a result of minor rotational shear strain involving plastic deformation with basal slip dominant. However, the presence of numerous very elongate quartz grains (affected generally by sub-grain formation) suggests a high strain which should have produced a very strong *c*-axis fabric if slip were the cause. Lister & Hobbs (1980), for example, show the main elements of a fabric become evident with a shortening of only 30%. It is necessary, therefore, to consider the relative roles of growth and plastic deformation. It seems possible, for example, that the dimensional quartz preferred orientation is primarily the result of growth just like the albite dimensional fabric. This is supported by the general lack of wrapping of quartz ribbons about feldspar grains, and the presence of ribbons in the shadow of feldspar (Fig. 5b). Initially a maximum of *c*-axes was probably oriented parallel to the lineation. Superimposed is a small strain accommodated by slip and sufficient in magnitude to create the weak lattice preferred orientation observed. If this interpretation is correct, the pre-existing dimensional preferred orientation would have been enhanced except where recrystallization has occurred.

The poles to (001) of the associated sheet silicates form a girdle about the lineation, with a strong maximum coinciding with the pole to the layering (Fig. 12b). The relative roles of growth and mechanical alignment of inequidimensional grains, the two most likely causative factors, are difficult to assess. The grain-size of the sheet silicates clearly indicates grain coarsening during metamorphism, and the interlocking of grains indicates the importance of growth mechanisms. Growth anisotropy of sheet silicates can produce a preferred orientation (Vernon 1976, Ishii 1988). On the other hand, the sheet silicate-rich layers probably represent in part a residue from which quartz has been dissolved during strain; the resultant volume loss would inevitably have oriented existing sheet silicates which in turn could have acted as seeds during grain growth.

CONCLUSIONS AND DISCUSSION

Textural evidence of euhedral terminations and non-rotated twin planes show that the albite dimensional and crystallographic preferred orientations in the Haast Schists result from competitive anisotropic growth rather than plastic deformation during metamorphism. The process possibly involved stress-driven solution with precipitation in areas of extension during the formation of metamorphic layering. There is little evidence for plastic deformation of feldspar which is in accord with experimental and natural observations that indicate

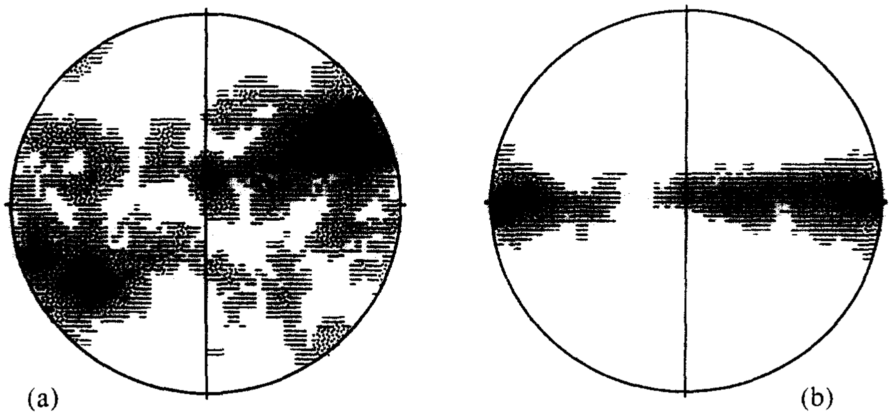

Fig. 12. Contoured lower-hemisphere equal-area projections to show (a) distribution of quartz *c*-axes, and (b) poles to (001) of the sheet silicates. For (b), in order to avoid 'blind spots', the poles to (001) were measured in the section perpendicular to the lineation, then rotated to the position shown. Contours in (a) at 1%, 2.3% and 3.6% per 1% area (max. 4.7%), and in (b) at 2%, 6%, 10% and 14% per 1% area (max. 14.5%). Number of poles in (a) 300, in (b) 200. Lineation and foliation positions as for Fig. 9.

feldspar is brittle at conditions of low-grade metamorphism.

The preferred orientation is the same as that found in higher grade metamorphic rocks, and the question needs to be asked whether growth or slip mechanisms dominate at higher temperatures. It cannot be assumed that the operation of a slip mechanism necessarily means it is the causative mechanism for forming an associated preferred orientation (Shelley 1986, Olsen & Kohlstedt 1986). Yet the explanation of feldspar fabrics in regionally metamorphosed rocks is often solely based on that assumption.

It is indisputable that many strong quartz preferred orientations form through the operation of slip (Price 1985). The Haast Schist quartz *c*-axis fabric is probably the result of a dominant basal slip during rotational shear stress, but the fabric is not as strong as the finite strain inferred from the dimensional preferred orientation would lead one to expect. The initial growth of quartz during extension at new sites to form metamorphic layering was probably characterized by a preferred orientation of growth origin. The initial dimensional fabric has been enhanced by secondary processes of plastic deformation, whereas the initial growth *c*-axis fabric has been destroyed.

Likewise, growth mechanisms were probably an important although not exclusive factor in the development of the sheet silicate preferred orientation.

The successful application of plastic deformation mechanisms to quartz and calcite has tended to dominate the recent literature on metamorphic rock fabrics, yet these minerals constitute only a small part of metamorphic complexes. Given that feldspar makes up 50% of crustal rocks, and given that feldspar as well as other minerals such as the amphiboles and sheet silicates may form preferred orientations through primary crystallization, there is clearly a need for more work on growth fabrics.

Acknowledgements—I am grateful to Professor A. J. R. White for a critical reading of this paper during his time as Visiting Erskine Fellow at the University of Canterbury, and to the two referees whose comments led to many improvements.

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