

A PROVISIONAL STRUCTURAL THICKNESS MAP OF THE OTAGO SCHIST, NEW ZEALAND

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ABSTRACT. Metamorphic zones, terranes and lithologic associations provide a subdivision of the lithologically monotonous Otago Schist on a 10 to 50 kilometer scale. In this study, form line maps of schist foliation have been used to construct a provisional structural thickness map of the Otago Schist that allows a more detailed (1-5 km scale) subdivision of the entire schist. The map shows the macroscopic thickness of schist measured orthogonal to dominant foliation, relative to the datum of the Caples-Rakaia terrane boundary. The structural thickness map provides a new spatial reference frame for the Otago Schist that depicts the differing levels of exhumation of penetratively deformed metamorphic rocks. The structural thickness parameter shows a good correlation with metamorphic grade, white mica grain size, and K-Ar and Ar-Ar ages, thus justifying the simplifying assumptions behind the map's construction. The map reveals several hitherto little-highlighted features including along- and across-strike correlations, interference patterns between Mesozoic and Cenozoic macroscopic folds, net displacement across known and inferred major faults, and relative structural position of mesothermal gold deposits.

INTRODUCTION

Haast Schist is the name given to a belt of schist in New Zealand that overprints the western edge of the Rakaia (Older Torlesse) Terrane. Haast Schist is subdivided geographically, the two best known parts of the belt being the Alpine Schist, a 20 kilometer wide strip of amphibolite facies rocks exhumed along the Alpine Fault in the Neogene, and the Otago Schist (fig. 1). The Otago Schist forms an approximately 150 kilometer wide structural arch ranging from prehnite-pumpellyite facies on the flanks to greenschist facies (garnet-biotite-albite zone) in the center (fig. 1; Turnbull, 2000; Mortimer, 2000). The Otago Schist represents the deepest exhumed parts of a Late Paleozoic-Mesozoic accretionary prism that formed along the south Gondwana margin facing the paleo-Pacific Ocean. The schist consists of the deformed and metamorphic equivalents of the Rakaia and Caples Terrane graywackes of Permian to Late Triassic depositional age and Jurassic-Cretaceous metamorphic age (Wood, 1978; Mortimer, 1993a; Breeding and Ague, 2002). It is crosscut by numerous, gold-bearing quartz vein systems and shear zones (Craw and Norris, 1991).

The Otago Schist is dominated by psammitic and pelitic greyschist with subordinate bands of greenschist and quartzite, and very rare pods of marble and ultramafic schist. Like many accretionary complexes, the Otago Schist lacks a 1 to 10 kilometer scale lithostratigraphy. Regional geological mapping of the Otago Schist has been based on criteria such as terranes, lithologic associations, metamorphic zones, and textural zones (fig. 1; see also MacKenzie and others, 1999). Such criteria, except for textural zones, are widely used to subdivide metamorphic belts elsewhere. Textural zones (TZs) are empirical field and petrographic subdivisions of schist based on progressive development of foliation and segregation, and concomitant increasing grain size of metamorphic quartz and mica (Hutton and Turner, 1936; Bishop, 1972; Turnbull and others, 2001). Five textural zones can be defined in Otago; the boundaries of textural zones are gradational and are called isotects (Bishop, 1972). Textural zones have been used in New Zealand since the 1930s but have seen little use elsewhere. Each of the aforementioned mapping criteria has allowed subdivision of the Otago Schist into between three and six units that reveal broad (10-50 km) scale

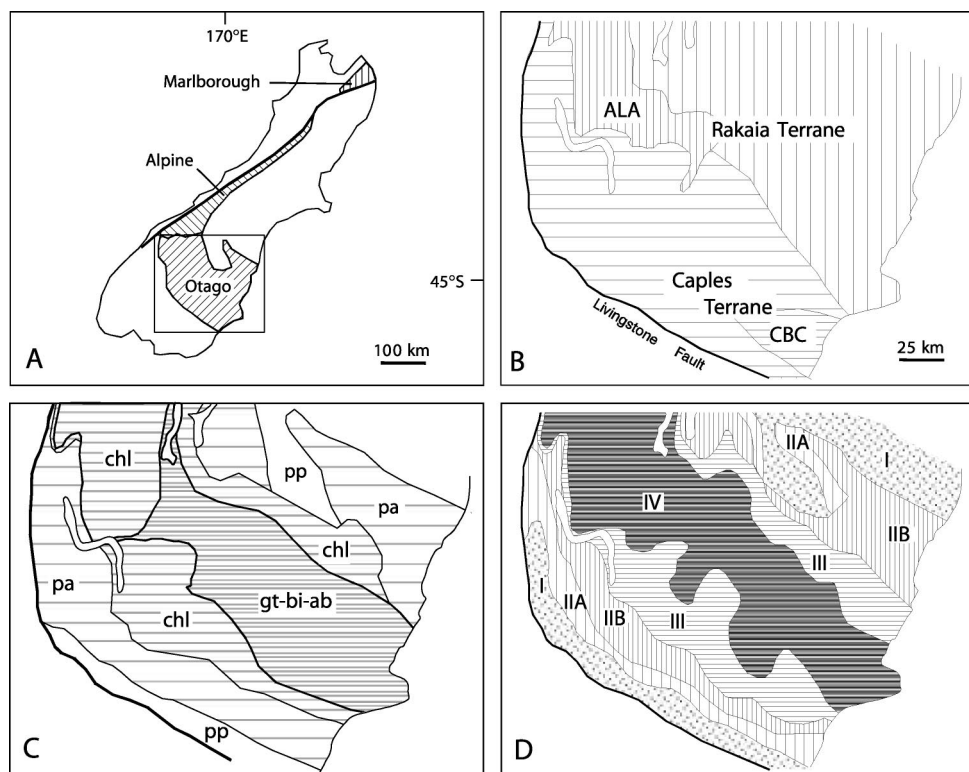


Fig. 1. (A) Location of the Otago Schist, South Island, New Zealand. Different parts of the Haast Schist belt shown with different line patterns. (B) Lithotectonic subdivision of the Otago Schist. Aspiring lithologic association (ALA) and Chrystalls Beach Complex (CBC) are here treated as subunits of the Rakaia and Caples Terranes respectively (Mortimer, 1993a; Coombs and others, 2000). (C) Metamorphic zones in the Otago Schist after Mortimer (2000). Map symbols: pp, prehnite-pumpellyite facies; pa, pumpellyite-actinolite facies; chl, greenschist facies chlorite zone; gt-bi-ab, greenschist facies garnet-biotite albite zone. Note broad antiformal symmetry of metamorphic zones. (D) Textural zones (TZs) in the Otago Schist after Bishop (1972) and Turnbull and others (2001). TZI is unfoliated graywacke, and TZIIA incipiently foliated schist. With increasing textural grade to TZIV, schist becomes progressively more foliated and segregated.

aspects of the internal structure of the outwardly featureless and monotonous Otago Schist (fig. 1). To date, a regional subdivision of the schist based on structural data has not been made.

Geological basement of the Caples and Rakaia terranes underlies an area of more than 30000 km² in Otago. Figure 2 shows generalized dips of foliation in the Otago Schist, the flanking Caples and Rakaia graywacke, the position of the intra-schist terrane boundary, and the distribution of unconformably overlying sedimentary rocks. The dominant, pervasive foliation in much of the eastern Otago Schist is subhorizontal and deviates only 0 to 20° from the attitude of the subdued, present day land surface (fig. 3). In this area, the present day land surface coincides with a well-preserved, areally extensive, low-relief Late Cretaceous erosion surface (figs. 2 and 3; LeMasurier and Landis, 1996; Turnbull, 2000; Forsyth, 2001, and references therein). This erosion surface is also cut into the Albian terrestrial graben deposits that depositionally overlie the schist (fig. 2) and is manifested outside Otago as a widespread approximately 85 Ma marine unconformity (Crampton and others, 1999). The implication of the figure 3 cross section is that, by the Late Cretaceous, at least 10000 km² of greenschist facies

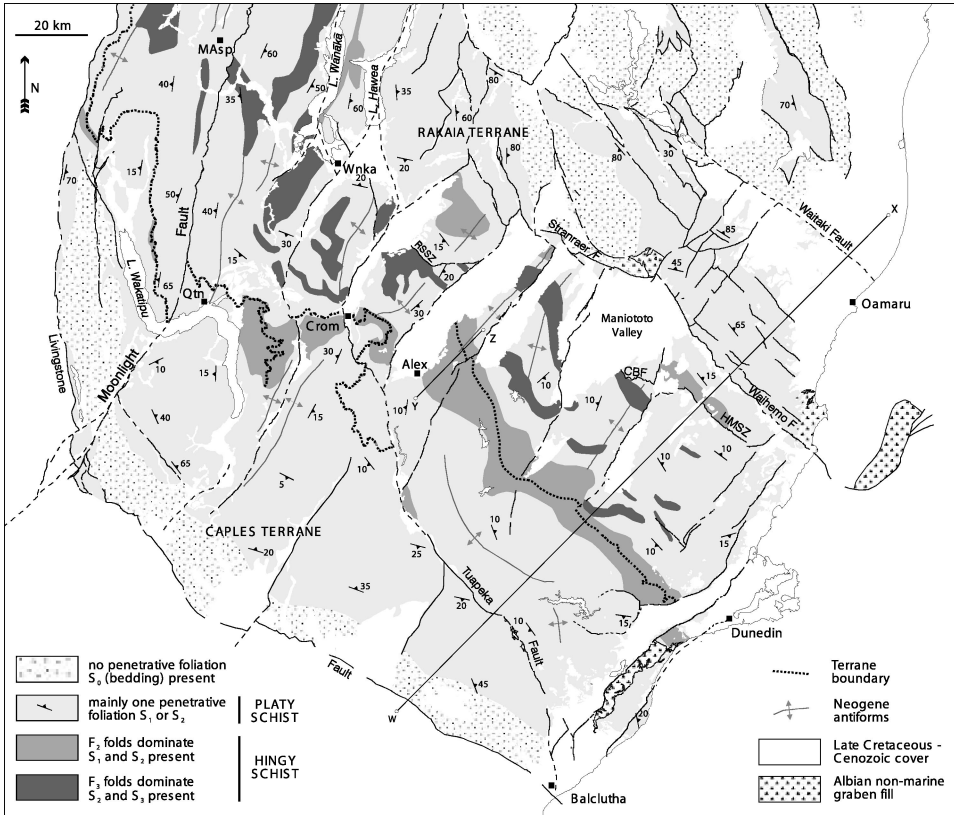


Fig. 2. Geological map of Otago showing major Neogene faults and folds, degree of penetrative fabric development in the Otago Schist, and regions in which mesoscopic folds are either abundant or near absent (areas of hingy and platy schist respectively). All changes in fold vergence occur within regions of hingy schist but, in terms of area and volume, hingy schist is seen to be much less extensive than platy schist. Typical dips of foliation in regions of platy schist are shown by strike and dip symbols. Map compiled from data in QMAP database (Bishop and Turnbull, 1996; Turnbull, 2000; Forsyth, 2001), which includes that of Brown (1968), Turnbull (1981), Crow (1985), Mortimer (1993a), and MacKenzie and others (1999). Compare with fold axis summary and stretching lineation trajectories given by Mortimer (1993b, figs. 2-4). Map symbols: MAsp, Mount Aspiring; Qtn, Queenstown; Crom, Cromwell; Alex, Alexandra; Wnka, Wanaka; RSSZ, Rise-and-Shine Shear Zone; HMSZ, Hyde-Macraes Shear Zone; CBF, Cap Burn Fault.

rock had been exhumed between the Waiheke and Livingstone Faults, with much of the regional foliation in a subhorizontal attitude, and parallel to the highly-strained, intra-schist Caples-Rakaia Terrane boundary. The uniformity of metamorphic grade between the Waiheke and Tuapeka Faults precludes significant rotation of foliation and indicates that foliation was not only exhumed, but also likely formed, in a subhorizontal attitude. Since the Late Cretaceous, Neogene warps and faults that increase in intensity westward towards the active plate boundary deformed both the erosion surface and the schist foliation (fig. 2).

The simple regional Otago Schist geometry outlined above and presented in figure 3 invites an analysis of the exposed structural thickness of the schist. In this paper I present a provisional structural thickness map of schist with a pervasive foliation measured orthogonal to the regional datum of the Caples-Rakaia Terrane boundary. I describe the methods and assumptions behind map construction, outline what aspects of schist geology the map reveals, and discuss the various new issues that

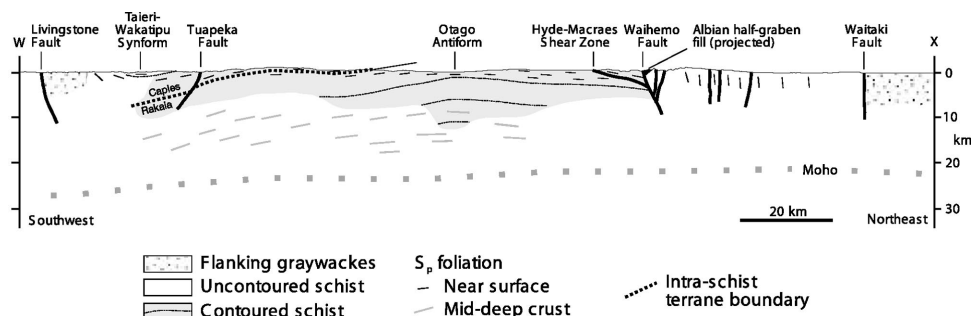


Fig. 3. Crustal cross section along line WX in figure 2. Present day land surface approximates to that of a Late Cretaceous erosion surface. No vertical exaggeration. Near surface geology from figure 2; mid-deep crustal interpretations from Mortimer and others (2002). Note change in legend from figure 2: gray shading shows limits of S_p structural thickness contouring for this paper and is restricted to regions where S_p is probably subparallel to the Caples-Rakaia Terrane boundary. Taieri-Wakatipu Synform and Otago Antiform are not shown on figure 2 but are discussed later in the text. In the context of the Otago Schist as a Mesozoic accretionary wedge, the toe of the wedge (Pahau Terrane) and trench would be situated northeast of the section line and the arc (Median Batholith) to the southwest (Mortimer and others, 2002).

arise from the exercise. The structural thickness map is based on a form line map and is an alternative way of projecting structure contour data on a regional scale. The condition that schist foliation initially formed in the same (in this case, subhorizontal) attitude sets geologic and geographic limits to the exercise (shaded area in fig. 3). The structural thickness map provides a new and useful empirical spatial framework for strain, thermochronological and mineral deposit studies. It emphasizes the three-dimensional nature of the Otago Schist, and shows how subsequent non-penetrative major folds and major faults have affected the penetratively deformed and thinned schist pile. The methods used here may be applicable to other orogenic belts that contain subhorizontal foliated rocks.

MESOSCOPIC AND MACROSCOPIC STRUCTURE IN OTAGO

Early geologists had a stratigraphic approach to schist geology and described the Otago Schist in terms of thickness as one might treat a simple sedimentary pile. For example, Park (1909) estimated thicknesses for schists of about 3300 meters near Alexandra, up to 3600 meters near Cromwell and up to 4500 meters near Queenstown (fig. 2). Workers in the 1960s (for example Wood, 1963; Means, 1966; Brown, 1968) started to attach significance to widespread mesoscopic folds and recognized the considerable deformation undergone by the meta-sedimentary rocks. Much subsequent work has focused on mesoscopic fold generations as the key to describing and interpreting schist structure (Turnbull, 1981; Craw, 1985). Brown (1968), Turnbull (1981), Craw (1985) and Cox and others (2000) pointed out the difficulties in correlating fold generations across Otago, in particular in distinguishing between S_1 and S_2 , S_2 and S_3 , and F_2 and F_3 in various areas. In an attempt to circumvent this problem, Craw (1985) introduced the concept of pervasive foliation, with symbol S_p , as a useful and practical way to describe dominant foliation in parts of the Otago Schist irrespective of structural generation.

Platy and Hingy Schist

Figure 2 shows a simple division of Caples and Rakaia rocks into non-schistose graywacke and argillite (approximately 15% by basement area), unfolded or little-folded “platy” schist (74%) and strongly mesoscopically folded “hingy” schist (11%).

Nonschistose rock.—Unfoliated to weakly foliated areas of prehnite-pumpellyite to pumpellyite-actinolite facies graywacke and argillite are known in New Zealand as textural zone I (Bishop, 1972; Turnbull and others, 2001). Within these areas bedding (S_0) is folded by F_1 folds and an incipient, though non-penetrative, S_1 axial planar cleavage can be present. As the rocks grade into TZIIA schist, bedding (S_0) becomes transposed into parallelism with S_1 .

Platy schist.—Areas where one pervasive foliation (S_p) dominates can be described as platy schist. This type of foliation occurs where F_2 or F_3 mesoscopic folds are either absent, or where F_2 or F_3 folds have such small amplitudes and wavelengths that the lithologic layering form surface is effectively subparallel (approximately $<20^\circ$) to foliation, or else F_2 and F_3 folds are tight and isoclinal to rootless such that the lithologic layering form surface is effectively subparallel to a new S_p foliation. The latter situation probably applies in the central portions of the schist between Mount Aspiring, Queenstown, Dunedin and the Maniototo Valley. Photographs of platy schist are given in Turnbull (1981, figs. 2, 3, 4, and 8AGH). In platy schist regions, rock tors are tabular and S_p dip slopes are clearly defined (for example Coronet Peak skifield, 15 km north-northeast of Queenstown). Figure 2 shows that some seven eighths of the area of the Otago Schist comprises structurally homogeneous regions of platy schist.

Hingy schist.—Regions of hingy schist are where F_2 or F_3 mesoscopic folds dominate exposures such that there is a significant (approximately $>20^\circ$) angle between the lithologic layering form surfaces and axial planes of folds; both early and late foliations are recognizable and of subequal intensity. Photographs of hingy schist are given in Turnbull (1981, figs. 8BCDEF and 13) and Craw (1985, fig. 6). Rock tors in hingy areas tend to be irregular in shape and mountain ranges tend to be craggy and lack cuestas (for example Cardrona skifield mid-way between Wanaka and Queenstown, Remarkables skifield 12 km east of Queenstown). Despite the considerable attention they have received, areas of structurally complex hingy schist comprise only about one eighth of the exposed area of the Otago Schist, and have clear vertical and lateral limits with respect to adjoining platy schist (fig. 2). The volumetrically largest region of hingy schist appears to be a zone of mainly northeastward-vergent F_2 mesoscopic folds in the vicinity of the Caples-Rakaia Terrane boundary between Queenstown and Dunedin.

Interpretation of Mesoscopic Folds

At present there are two alternative models that describe the relationship and significance of mesoscopic folds to macroscopic structure in Otago Schist. These can be illustrated by sketch profiles along a section of schist across the Caples-Rakaia boundary near Alexandra (YZ in figs. 2 and 4; see also Means, 1966). The profile in figure 4A shows the change in mesoscopic fold geometry that is observed down section (up-metamorphic grade) from southwest to northeast. Gently southwest-dipping platy (S_p) Caples schist grades into a zone of hingy transposed schist towards the terrane boundary in which form surface and axial planar cleavage both define foliations. Across into the Rakaia Terrane, mesoscopic folds tighten and the axial planar foliation develops into S_p also with a gently southwest-dipping attitude.

By far the majority of authors (for example Brown, 1968; Turnbull, 1981; Craw, 1985; Cox, 1991; Winsor, 1991) would interpret this profile as shown in fig. 4B (after Means, 1966, fig. 5 upper part). In this model platy S_1 schist becomes involved in an F_2 macroscopic recumbent fold, and becomes totally transposed into S_2 platy schist in the lower limb of the fold; the hingy mesoscopic fold vergence change defines a macroscopic fold closure. The kinematic transport direction is perpendicular to the low-strain fold axes (b-type folds). For most of the distance between Dunedin and Queenstown (fig. 2), S_1 and S_2 foliations can be satisfactorily discriminated either side of this zone of F_2 folds. However, north of Queenstown, and southwest of Alexandra, F_2

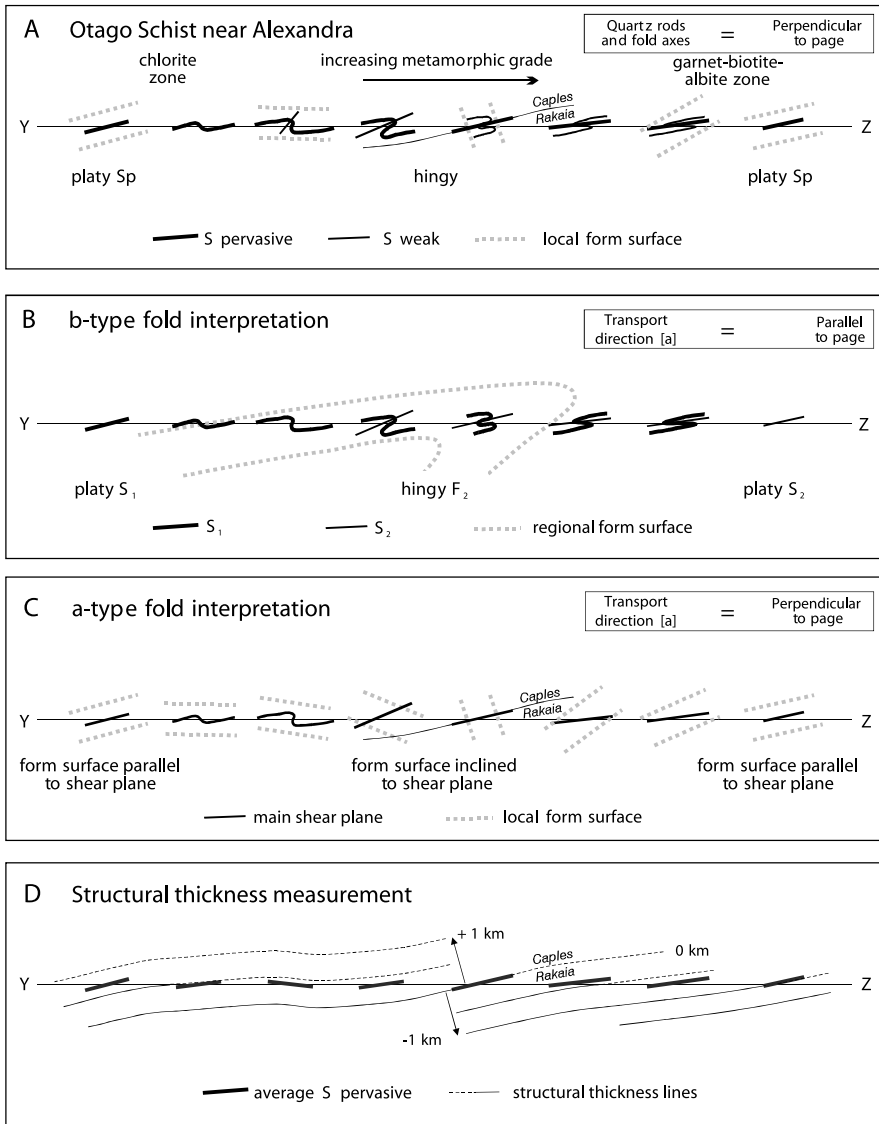


Fig. 4. Sketch profiles in the Otago Schist near Alexandra, along section YZ in figure 2 illustrating mesoscopic and macroscopic structure. Not to scale. (A) Field observations of northwest metamorphic grade increase and two zones of platy schist separated by a zone of hinging schist. (B) Interpretation that mesoscopic folds are b-type folds whose vergence changes allow definition of a macroscopic recumbent fold with a translation direction parallel to the page. There is a progression from S_1 to S_2 via F_2 macroscopic recumbent fold (for example Means, 1966 fig. 5 upper part; Turnbull, 1981; Cox, 1991). (C) Interpretation that mesoscopic folds are a-type folds that have limited kinematic significance and that translation direction is parallel to prominent stretching lineations (perpendicular to page). Pervasive foliation S_p is locally perturbed by a-type folds but a new foliation generation is not necessary (for example Means, 1966, fig. 5 middle part; Malavieille, 1987; Mortimer, 1993b). (D) Method, adopted in this paper, of measuring structural thickness orthogonal to pervasive foliation (S_p) relative to the Caples-Rakaia boundary. In zones of hinging schist, the average attitude of S_p foliation (fig. 4C) is used. Figure 4D can be projected onto the left central part of figure 3.

folds are absent which poses a problem in the identification and definition of S_1 and S_2 , and thus in the general (as opposed to local) applicability of the multiple deformation generation model in Otago.

An alternative mesoscopic fold interpretation (Mortimer, 1993b) is given in figure 4C (after Means, 1966, fig. 5 middle part). In this the mesoscopic folds, because they are parallel to quartz rod stretching lineations, are interpreted as a-type folds (Mattaueer and others, 1983; Malavieille, 1987) unrelated to a macroscopic fold. These authors and Berthé and Brun (1979) and Lacassin and Mattauer (1985) have emphasized that, in the ductile regime, folds need not form or remain perpendicular to the transport direction; folds can initiate subparallel to the transport direction if competent layers are inclined to the shear plane (as in fig. 4C). In this interpretation multiple fold and foliation generations are de-emphasized in favor of an essentially single, progressive, penetrative deformation model for the Otago Schist (Mortimer, 1993b). The importance of the interpretation of mesoscopic folds to the present paper is discussed below.

STRUCTURAL THICKNESS MAP CONSTRUCTION

Form line maps of foliation or schistosity (also known as foliation trajectory or form surface maps) are commonly drawn to indicate the regional structural grain of a region in a qualitative, pictorial fashion (for example, Hobbs and others, 1976; Butler and Coward, 1984; Leblanc and others, 1996; Stephenson and others, 2001). Quantitative measurements of structural thickness along cross section lines, that is 1 to 10 kilometer scale profiles of metamorphic rocks measured orthogonal to foliation from a geological contact, are also common in the literature (for example, King, 1986; Grapes and Watanabe, 1992; Miller and others, 1992; Argles and others, 1999) and have been used to demonstrate the collapse of isograds through ductile thinning. Structure contour maps are used to depict the elevation of a geological contact orthogonally above or below a reference surface, usually a horizontal plane such as sea level (Hobbs and others, 1976). In this paper I have combined these three simple techniques to produce a structural thickness map that shows where structural thickness contours, measured orthogonally from a geological marker horizon, intersect the land surface.

In making such a map, there are a number of important steps:

1. Construction of form line maps from a sufficiently densely populated dataset.
2. Choice of a suitable regional reference horizon.
3. Adoption of consistent methods for measuring structural thickness across folded areas.
4. A means of tracking structural thickness levels across faults and areas of no exposure.
5. Recognizing the limitations of the exercise.

Each of these steps poses its special problems in the Otago Schist. The approaches adopted for this study were as follows.

The QMAP Dataset

The starting point for the present exercise was a digitized dataset of some 12000 published and unpublished Otago Schist foliation measurements. This data set had already been compiled in a Geographic Information System (GIS) for the Institute of Geological and Nuclear Sciences' new 1:250000 scale geological map of New Zealand: the QMAP project (Bishop and Turnbull, 1996; Cox and others, 2000; Turnbull, 2000; Forsyth, 2001). The entire QMAP foliation dataset for Otago was plotted using standard foliation symbols at 1:250000 scale on topographic maps with a 100 meter contour interval. Form line maps of schist foliation were drawn by hand on the plot, interpolating in areas of low sample density. Major faults and fold axial traces were also extracted from the QMAP GIS and appropriate offsets and/or deflections were made

in the form lines at these features, as well as at others discovered during the form line mapping exercise.

Choice of Reference Horizon

Greenschist marker bands are rarely traceable for more than 1 to 5 kilometers, so cannot be used as regional reference horizons. The Caples and Rakaia Terranes are two of the main tectonostratigraphic terranes of New Zealand, and are distinguished largely by consistent differences in detrital modes and petrochemistry (Mortimer and Roser, 1992). They were amalgamated in the Otago Schist accretionary complex with the Rakaia terrane underthrusting the Caples Terrane from the paleo-trench side (fig. 3). Ultramafic pods are present in places near the boundary (Mortimer, 1993a). The terrane boundary is always within the greenschist facies and is strongly overprinted by the schist foliation.

The Caples-Rakaia Terrane boundary (figs. 2 and 3) was chosen as a reference horizon for the structural thickness map because it is a classic, highly strained pre-tectonic marker whose geometry is clearly controlled by regional S_p (Cox, 1991; Mortimer and Roser, 1992; Mortimer, 1993b). The position of the boundary as proposed by Mortimer and Roser (1992) has been tested and refined by the QMAP program over the last few years (MacKenzie and others, 1999; Turnbull, 2000). The boundary extends across the whole of Otago, largely coincides with the TZIII–IV isotect (fig. 1; Turnbull and others, 2001) and its position is actually known with greater precision than most isograds from other places.

Whole rock K-Ar and white mica Ar-Ar profiling near Queenstown and Dunedin give ages at the terrane boundary between 135 and 145 Ma (Graham and Mortimer, 1992; Adams and Robinson, 1993; Little and others, 1999), thus indicating a similar cooling history for the chosen reference horizon in areas 200 kilometers apart.

Structural Thickness of Schist in Folded Areas

In areas of platy schist, it is straightforward to convert a form surface map of S_p to a structural thickness map (for example extreme ends of the sections in fig. 4). As an example, cross sections shown by Craw (1985, figs. 9 and 12) reveal thicknesses of schist, measured perpendicular to S_p , of several kilometers west of Lake Wanaka. In the one eighth of the Otago Schist that is hinged, the methods employed in the conversion depend on the fold model adopted (see above, fig. 4). As the simplest possible approach to drawing structure contours of foliated schist, the present study uses the model of figure 4D, derived from figure 4C, in which macroscopic recumbent folds are ignored. Instead, the thickness of schist with average to typical pervasive foliation, S_p is drawn throughout the zone of hinged schist as shown in figure 4D. Even within most zones of hinged schist, one of the foliations is usually clearly the dominant planar fabric. If the interpretation of figure 4B is adopted, then structural thickness of schist with S_p could still be estimated but allowances of the net amount of thinning or thickening across each macroscopic fold would have to be made. Hypothetically, if structural thickness doubled due to macroscopic recumbent folding then the structural thickness obtained using figure 4D would overestimate true structural thickness in zones of hinged schist by a factor of two. The dominance of platy over hinged schist (fig. 2) means that this overestimate of true structural thickness is not likely to be a major problem in Otago.

Fault Block Correlations

The northern and eastern parts of the schist are separated from the Caples-Rakaia reference horizon by faults and/or regions of no schist exposure. Assignment of schist northeast of a line joining Lake Wanaka, Rise and Shine Shear Zone, Stranraer Fault, Cap Burn Fault and Hyde-Macraes Shear Zone (fig. 2) to the correct thickness above or below the reference horizon was made using textural grade and white mica grain size.

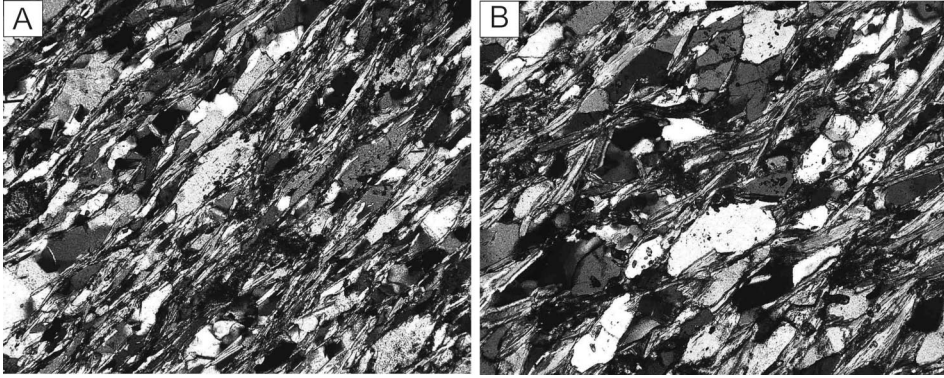


Fig. 5. Photomicrographs of tectonically juxtaposed psammitic gray schists showing different metamorphic white mica and quartz grain sizes. (A) sample P63785, TZIII from hangingwall (north side) of Rise and Shine Shear Zone, typical mica thickness (estimated by eye over entire section, perpendicular to foliation) $\sim 20 \mu\text{m}$. (B) sample P63787, TZIV from footwall (south side) of Rise and Shine Shear Zone, typical white mica thickness $\sim 40 \mu\text{m}$. Both photos cross-polarised light, width 3.4 mm.

Turnbull and others (2001) made the observation that through textural zones IIA, IIB, III and IV, typical white mica grain thickness, as measured perpendicular to foliation, increases from $<5 \mu\text{m}$ to $\sim 50 \mu\text{m}$ (figs. 5 and 6). White mica grain diameter, measured parallel to foliation, also shows an increase. Furthermore, Turnbull and others (2001) showed this grain size change was largely independent of psammitic or pelitic lithology and of Caples or Rakaia terrane affiliation.

For the present study, I have investigated the variation of mica grain size in 616 graywacke, platy schist and hinged schist samples from the area of figure 2. The average thickness of metamorphic white mica grains was estimated, by eye, to the nearest $5 \mu\text{m}$ in thin sections cut perpendicular to foliation. In figure 6 these results are plotted against the structural thickness parameter (orthogonal thickness of S_p above (+) or below (-) the Caples-Rakaia reference horizon, as measured using the method of fig. 4D and used to construct fig. 7). Figure 6 shows that there is a reasonably good empirical relationship between mica grain size and structural thickness such that, for mica grain thicknesses in the range 5 to $40 \mu\text{m}$, the average white mica grain thickness of samples can be used as a proxy for the relative structural thickness parameter in the interval +5 to -5 kilometers. The following very approximate relationship holds:

$$D = 7.5 - 0.3t \quad (1)$$

Where D is the structural thickness parameter (km) and t is white mica grain thickness (μm). Equation (1) only applies within the grain size and S_p thickness limits specified above. In using this relationship to correlate structural thickness between fault blocks, populations of samples, spread throughout a continuous schist section, should be used; individual grab samples will likely give spurious results.

A detailed discussion of the reasons for the irreversible increase in mica grain size with various depth and grade parameters in the Otago Schist is beyond the scope of this study. However, the relationship holds across profiles of hinged schist (for example, fig. 4D) and is consistent with observations that, in the Otago Schist, geometric reorientations of the early-formed " S_1 " surface (for example to " S_2 " attitudes) proceed via crenulation of existing micas and not via nucleation and growth of a new generation of S_2 micas (Turnbull, 1981; Craw, 1985; Mortimer, 2000).

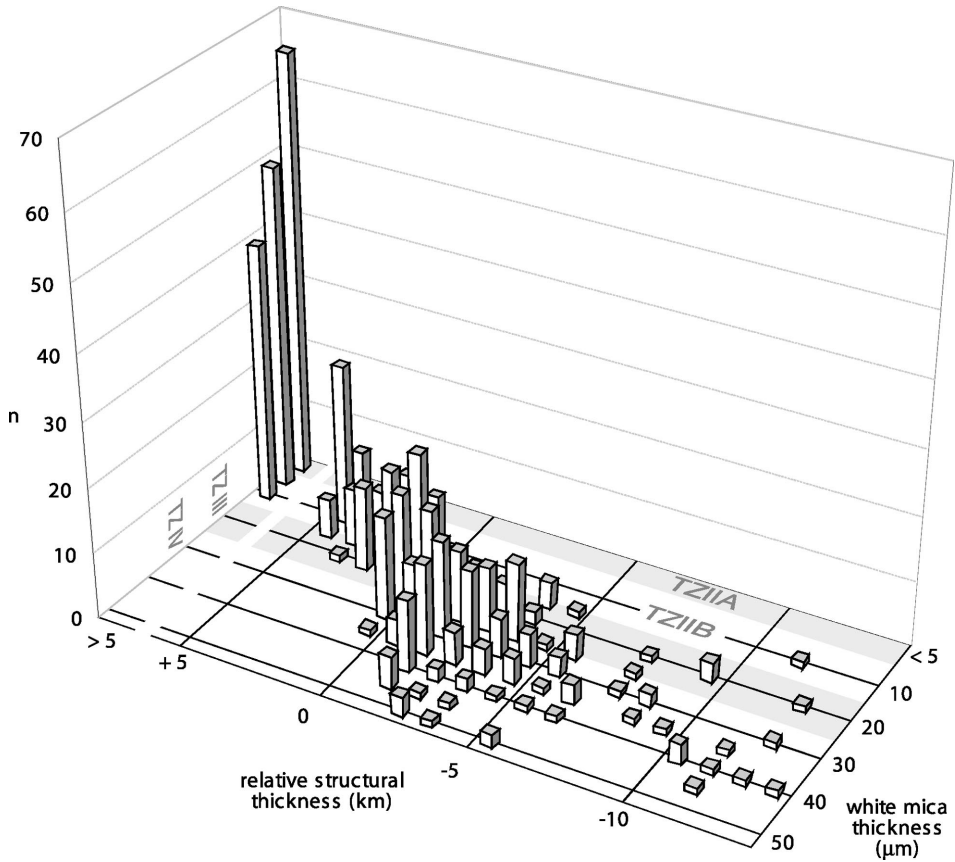


Fig. 6. Histogram showing relationship between typical white mica grain size and structural thickness parameter of 558 Otago Schist samples. White mica grain thickness was obtained from visual estimates, made to the nearest 5 μm , of thin sections cut perpendicular to S_p . Structural thickness S_p to the nearest 1 km was obtained from fig. 7. Note break in structural thickness scale above +5 km. Mica grain size correlates with textural zone (Turnbull and others, 2001), and with the structural thickness parameter. Measurements from 58 Caples and Rakaia graywackes (textural zone I) are not shown; these all have white mica grain size $<5 \mu\text{m}$.

Limits of Contouring

The provisional structural thickness map of rocks featuring a dominant foliation orthogonal to the Caples-Rakaia Terrane boundary in the Otago Schist is shown in figure 7¹. Using the methods outlined above, S_p was contoured at 1 kilometer intervals of structural thickness relative, and orthogonal, to the 0 kilometer Caples-Rakaia reference horizon (above = positive values, below = negative). The deepest levels of the schist on figure 7 are at about -15 kilometers relative to the Caples-Rakaia boundary. Still deeper levels might be expected in the Alpine Schist to the north (Grapes and Watanabe, 1992).

Parts of the schist structurally higher than +5 kilometers were not contoured because, towards the lower grade flanks of the schist, it is less certain that the requirement that S_p formed parallel to the Caples-Rakaia boundary is fulfilled (white

¹ Color inkjet plots of the map at the original 1:500,000 compilation scale, and digital GIS files, are available on request from the author.

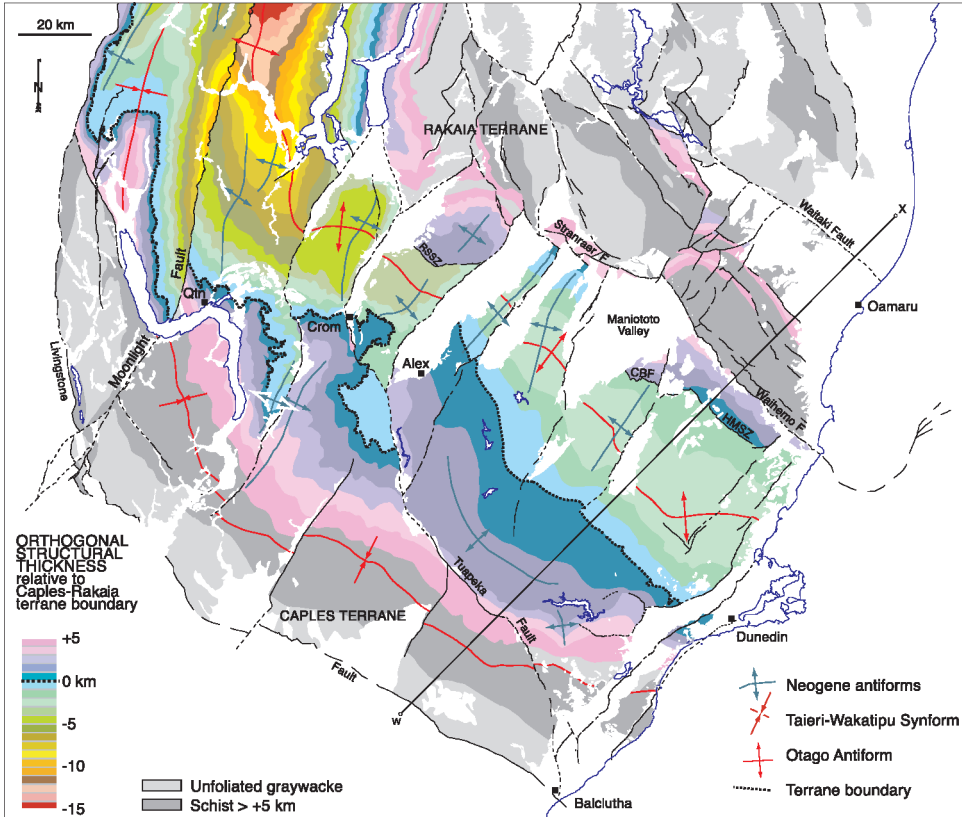


Fig. 7. Provisional structural thickness map of the Otago Schist. Contours at 1 km intervals on dominant regional foliation S_p orthogonally above (+) and below (-) the datum level of the Caples-Rakaia Terrane boundary. This datum is projected across the schist axis (Otago Antiform) into the Rakaia Terrane schist. The deepest structural levels of the schist are exposed at the northern edge of the map just east of the Moonlight Fault. See figure 2 for geologic and geographic features.

areas in fig. 3). In the Rakaia Terrane at the 0 to +5 kilometer levels, the increasing lateral distance from the terrane boundary reference horizon, and need to use mica grain size for correlation, lead to added uncertainty in the structural thickness estimates. There are numerous strike-parallel faults that make structural thickness assignment difficult and, northeast of the Waihemo-Stranraer Fault system (fig. 2), it is difficult to pick the direction of increasing metamorphic/textural grade in the steeply dipping schist. The S_p structural thicknesses assigned to Rakaia Schist between the Maniototo Valley and Waitaki Fault, and near Lake Hawea, are speculative.

In the Caples Terrane at the > +5 kilometer levels, the axis of the Taieri-Wakatipu Synform is present (figs. 3 and 7; Mortimer and Johnston, 1990; Mortimer, 1993b; Turnbull, 2000). This is an upright open synform of half wavelength approximately 8 to 15 kilometers, amplitude approximately 2 to 4 kilometers, and interlimb angle 90 to 150°. The synform is not a simple post-metamorphic warp because metamorphic and textural grade increase unidirectionally across the structure, despite the change in attitude of S_1 foliation. Structure contouring was not continued southwestward beyond the axial trace because it is likely that S_p foliation in this part of the schist is not parallel to the Caples-Rakaia boundary (fig. 3).

The contoured part of figure 7 does not address structural aspects of the transition from graywacke to schist. The provisional structural thickness map is internally geometrically consistent, though uncertainty of contours is probably ± 2 kilometers. The map is a highly derived, non-unique view of the schist that is unlikely to remain unchallenged in years to come.

DISCUSSION

A New View of the Otago Schist

Figure 7 is a way of depicting S_p foliation trend, dip and thickness that allows a finer scale subdivision of the Otago Schist than the criteria used in figure 1. It is a semi-quantitative structural framework for the Otago Schist that potentially has a variety of uses, for example in thermochronological modeling, geobarometry and mineral exploration. The structural thickness map reveals some hitherto little-highlighted regional features:

1. Areas of steeply dipping and shallowly dipping schist foliation are shown by closely and widely spaced S_p contours respectively.
2. The position of the axial trace of the main schist antiformal megaculmination (Wood, 1978; herein named Otago Antiform) is shown for the first time. This is subhorizontal in its eastern part and moderately plunging in its western part. The changing plunge results in broadly similar maximum exhumation levels of the schist east of Cromwell and progressively deeper maximum exhumation levels northwest of there.
3. The Caples Terrane does not project across the Otago Antiform axis to equivalent structural levels on the northeast side of the schist. This fact does not compromise the use of the terrane boundary as a regional datum for the thickness contouring exercise (textural grade/mica grain size versus depth relations are the same in both terranes) but simply emphasizes the restricted distribution of the Caples Terrane to just the backmost part of the Mesozoic accretionary prism.
4. There are broad interference patterns between the west-northwest to north-northwest trending, long wavelength Otago Antiform and the shorter wavelength generally north-northeast striking Neogene antiforms that, in part, define some mountain ranges.
5. Maximum east side down dip-slip separation of 6 to 10 kilometers can be estimated for the Moonlight Fault north of Lake Wakatipu. Faults with similar strikes further east have much smaller vertical displacements.
6. There is broad structural continuity of the gently dipping schist crustal section on the Caples (southwest) side of the Otago Antiform axis, as shown by lack of faults disrupting the structural thickness contours (see also fig. 3).
7. Significant fault disruption of the steeply dipping schist crustal section has taken place on the Rakaia (northeast) side of the Otago Antiform axis. This disruption has been both by low angle faults like the Hyde-Macraes and Rise-and-Shine Shear Zones and by high angle faults such as the Waihemo Fault. These three faults have demonstrable Cretaceous normal movement on them (Forsyth, 2001; Deckert and others, 2002a, and references therein). Most of the faults shown in figure 2 were activated or reactivated as reverse faults in the Neogene (Turnbull, 2000; Forsyth, 2001).

Published cross sections of the Otago Schist (Wood, 1963, 1978) show a generally shallow foliation in the center and steeper dips at the schist flanks. Figures 3 and 7 show the position of major faults and the Otago Antiform and Taieri-Wakatipu Synform, both of which are probably first-order features of the Mesozoic accretionary prism. The Otago Antiform marks the axis of maximum exhumation of the schist. The

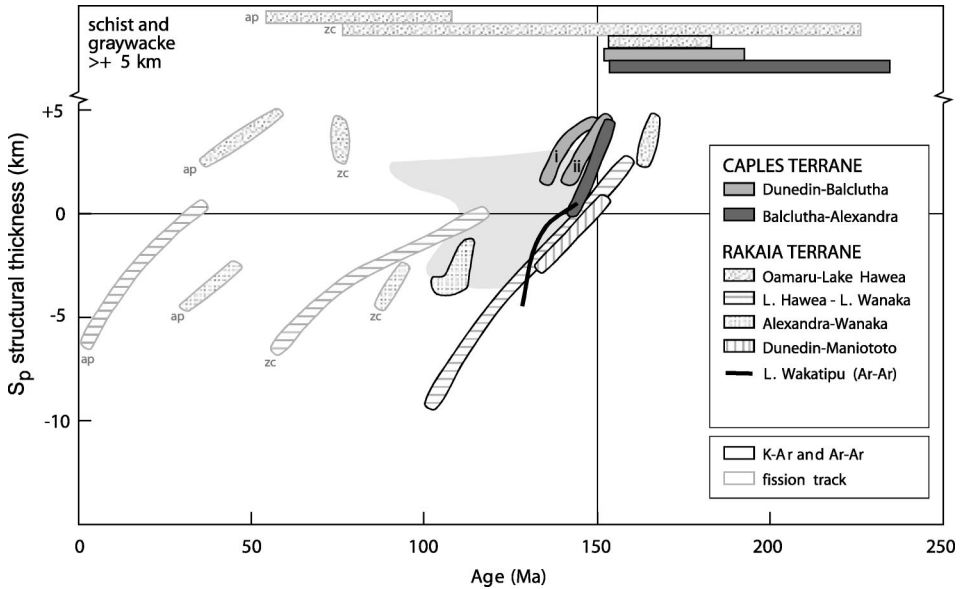


Fig. 8. Simplified summary plot of 220 Otago Schist radiometric ages versus the S_p structural thickness parameter. Scattered point arrays reduced (by eye) to best-fit curves based on geographic area and dating method. All curves are K-Ar whole rock or Ar-Ar white mica data except those labelled *zc* (fission track zircon) and *ap* (fission track apatite). 30 samples from various areas range to younger K-Ar ages than the curves (pale gray area). These include some obviously mineralized and/or hydrothermally altered rocks. Data from sources listed in the text and from Adams and Graham (2000), Nathan and others (2000), and Forster and Lister (2003).

Taieri-Wakatipu Synform might have arisen from differential movement of material (variable orientation of flattening strains) towards the rear part of the accretionary wedge.

Age-Depth Profiles

K-Ar and Ar-Ar age profiles through the Otago Schist have been presented by Adams and Gabites (1985), Adams and others (1985), Graham and Mortimer (1992), Adams and Robinson (1993), Little and others (1999), and Nishimura and others (2000). Little and others (1999) plotted age against structural thickness near the Caples-Rakaia Terrane boundary but in all the other cases, age was plotted against textural or metamorphic grade as a “depth” parameter. Limited fission track data have been reported by Kamp and others (1989) and Tippett and Kamp (1993a, b). Figure 8 is a plot of available geochronological data plotted against structural thickness of rocks with S_p obtained from figure 7. It can be considered an extended version of Little and others (1999, fig. 7). Several points emerge:

1. In any one area or profile, younger K-Ar ages occur at deeper structural levels. The inverse correlation of age with metamorphic grade has long been known (for example, Adams and others, 1985). The new Ar-Ar data of Forster and Lister (2003), from east of Cromwell, are at the young end of a continuum of ages.
2. Detrital contamination of Ar samples, and variable resetting of fission track samples, is a major problem in graywacke and schist from both Caples and Rakaia Terranes at $S_p > +5$ kilometers. Detrital contamination may also explain the difference in K-Ar ages between Rakaia and Caples schists in the

relative structural thickness interval $S_p = +1$ to $+5$ kilometers; detrital white micas are clearly visible in thin section in TZIIB Rakaia schists, less so in Caples schists.

3. There is a good correspondence between structural depth and maximum age such that an argon age, like mica grain size, may provide a useful proxy for S_p structural thickness over certain intervals, including across zones of hingy schist. In closely sampled profiles, this may provide the best way to identify cryptic, pre-Cenozoic, major faults in the schist. It may be that discrete ductile shear zones of differing ages are present in many parts of the schist (Forster and Lister, 2003). The pale gray area in figure 8 shows a widespread scatter of younger ages; some of these are from mineralized samples, but others, as yet, have no good geological explanation (Little and others, 1999).
4. The simplified argon age-relative structural thickness profiles are linear to slightly convex-up and thus support models of moderate exhumation rates since the Middle Jurassic rather than slow continuous cooling since the Early Jurassic (see Little and others, 1999, for a full discussion of this).
5. The sparse fission track zircon and apatite profiles also show a correlation of age with S_p thickness. This result indicates that parts of the Otago Schist were not finally exhumed until the Cenozoic, possibly with relatively uniform erosional stripping of the top few kilometers of crust.

An in-depth analysis of the diachronous cooling and exhumation history of the Otago Schist is beyond the scope of this paper.

Otago Schist Regional Architecture

The structural thickness of a rock mass is acquired during continuous and penetrative deformation by crystal-plastic flow and solution transfer mechanisms in the mid-crust. The net structural thickness of a body such as the Otago Schist is the end result of thickening by underplating at the base of the accretionary wedge and ductile thinning during foliation development (Ring and others, 1999). Structural thickness does not change when the rock mass translates or deforms by discontinuous and/or non-penetrative processes, for example by erosion, or by movement on kilometer spaced faults and folds in the upper crust. Thus the structural thickness map of the Otago Schist (fig. 7) depicts both the “frozen in” finite penetrative strain state of the Otago Schist and its subsequent exhumation and deformation by non-penetrative processes. The differing amounts of underplating and ductile thinning and their prolonged Jurassic-Cretaceous time of acquisition in different parts of the Otago Schist might seem to make figure 7 useless for any practical purpose. However, the correlation of the relative structural thickness parameter with metamorphic grade and with local K-Ar age profiles, even across zones of hingy schist, suggests that the map

1. can at least be used to qualitatively illustrate the exhumation pattern of the Otago Schist accretionary wedge;
2. has potential to be used as a new framework for strain and thermochronological data that could lead towards a quantitative exhumation map.

The near coincidence of the Late Cretaceous erosion surface with present day topography demonstrates that, south and east of Alexandra, the present day map pattern of the schist (fig. 7) closely approximates the Late Cretaceous exhumation geometry (north and west of Cromwell the steeper dips are the result of Neogene structures related to the Alpine Fault plate boundary). The Otago Antiform and Taieri-Wakatipu Synform are Mesozoic structures that define the broad architecture of the underplated and exhumed Mesozoic accretionary wedge. The Livingstone Fault can be regarded as a wedge backstop structure, and the lower grade Rakaia schists and graywackes extend off towards the northeastern toe of the wedge (fig. 3).

Norris and Bishop (1990) and Deckert and others (2002b) have presented strain data showing that parts of the Otago Schist were subjected to flattening strains of up to 70 percent. As more strain and thermochronological data become available, figure 7 can be used to extrapolate and interpolate these quantitative data in three dimensions throughout the paleo-accretionary wedge. In turn, this may help address the question as to which Otago Schist minerals, fabrics, and ages relate to “prograde” accretionary wedge underplating (Mortimer, 1993b) or to “retrograde” ductile thinning and exhumation (Forster and Lister, 2003), or to both processes.

An unknown thickness of Caples and Rakaia graywacke has been removed from the top of the schist pile. Estimates of pressures at peak temperature for rocks just below the Caples-Rakaia terrane boundary are imprecise but are in the range 0.7 to 0.8 GPa (Yardley, 1982) and 0.8 to 1.0 GPa (Mortimer, 2000). Thus schist exposed near the Cretaceous erosion surface records pressures of formation at 25 to 30 kilometers depth, approximately the same as the thickness of the present day crust (fig. 3; Mortimer and others, 2002). The recognized collapse of isobaths due to tectonic thinning in the Alpine Schist (Grapes and Watanabe, 1992) and elsewhere (Miller and others, 1992) cautions against a literal use of the Otago S_p structural thickness parameter to obtain even relative pressures across Otago. As new data emerge, steps and discontinuities in age profiles and metamorphic grade when plotted against the structural thickness parameter of figure 7 may reveal as-yet undiscovered accretion- and exhumation-related faults and folds in the Otago Schist.

Mineral Deposits

Both vein and shear-zone hosted mesothermal gold and tungsten deposits are present in the greenschist facies part of the Otago Schist (Craw and Norris, 1991). When plotted in a pseudo-cross section using the structural thickness parameter (fig. 9) it is observed that the deposits appear to fall into four groupings. The five Au-W lode deposits that occur on the Caples side of the Otago Antiform are also at the highest structural levels of any of the deposits. There are no mineral deposits at equivalent levels on the Rakaia side of the Otago Antiform, although scattered 0.1 to 1 meter thick semi-concordant quartz veins are relatively common in TZIIB–III Rakaia rocks (Mortimer, personal observation). Seven lode gold deposits in the Rakaia Terrane occur in gently dipping schist near the Otago Antiform axis between the 0 and –3 kilometer S_p thickness contours. Two Au lode systems in west Otago appear significantly deeper (fig. 9) and possibly provide an S_p thickness limit on the occurrences. The final grouping of gold deposits is of two shear-zone hosted systems on the Rakaia side of the Otago Antiform where net normal displacement on semi-brittle low angle faults, the Hyde-Macraes and Rise and Shine Shear Zones, has resulted in the excision of up to 2 to 4 kilometers of S_p structural thickness (fig. 5; Deckert and others, 2002a).

CONCLUSIONS

Digitized structural data from the Institute of Geological and Nuclear Sciences' QMAP database have been used to make a provisional structural thickness map of the Otago Schist. The map combines the familiar techniques of form line mapping, structural thickness estimation and structure contouring. Structural thickness contours of rocks with a dominant foliation, S_p , have been drawn orthogonal to a foliation-parallel reference horizon, the Caples-Rakaia terrane boundary that is believed to have formed in a subhorizontal attitude. Contouring of foliation over much of Otago is straightforward as most schist is mesoscopically unfolded and contains just one dominant S_1 or S_2 foliation. It is still possible to identify and contour S_p on a kilometer scale in the volumetrically minor parts of the Otago Schist that are strongly mesoscopically folded.

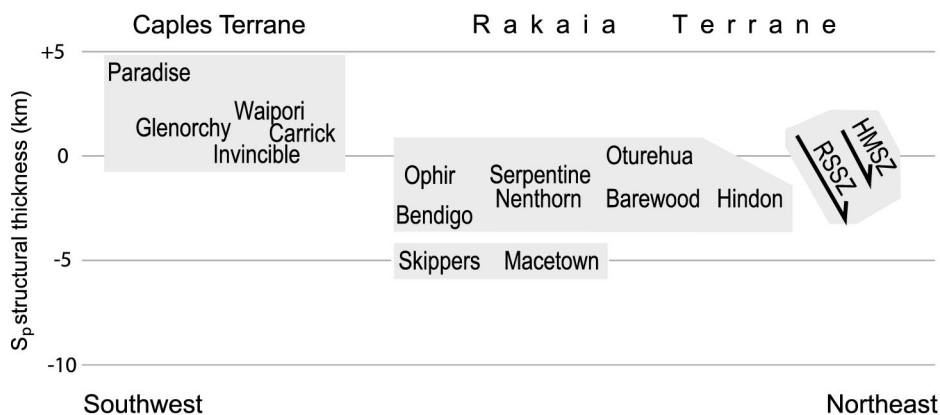


Fig. 9. Occurrences of Otago mesothermal Au and W mineral deposits (historical production >3 tonnes) in an S_p structural thickness framework. All deposits are vein-hosted except for Hyde-Macraes Shear Zone (HMSZ) and Rise and Shine Shear Zone (RSSZ). All deposits occur within the greenschist facies, none occur deeper than 5 km S_p structural thickness. See Craw and Norris (1991) or Mortimer (1993a) for locations.

An empirical relationship between white mica grain size (textural grade) and structural thickness of schist with S_p foliation provides a useful means to project the structural thickness contours across major faults. The well-known inverse relationship between metamorphic grade and apparent K-Ar age in the Otago Schist (Adams and others, 1985) is manifested as linear to slightly convex-up profiles on plots of age versus S_p thickness. The correlations between structural thickness of schist with S_p foliation, mica grain size, and Ar age provide a validation of the approaches taken to construct the regional structural thickness map.

The structural thickness map illustrates the finite penetrative strain state of the underplated and ductilely thinned Otago Schist Mesozoic accretionary wedge, as well as the Cretaceous to Neogene upper crustal non-penetrative exhumation pattern. The map emphasizes hitherto obscure structures in the Otago Schist, including the variable plunge of the main schist axis (Otago Antiform). The low grade part of the Caples (southwest) side of the schist shows an essentially structurally continuous section of gently dipping schist from the Taieri-Wakatipu Synform through to the Otago Antiform. In contrast, the low grade part of the Rakaia (northeast) side of the schist is steeply dipping and highly faulted. These features are preserved beneath a Late Cretaceous erosion surface in east Otago and are perhaps inherited features of the Mesozoic accretionary wedge. Net normal displacements of 1 to 10 kilometers can be estimated across low angle Cretaceous shear zones (Hyde-Macraes and Rise and Shine Shear Zones) and across Neogene faults (Moonlight Fault). The structural thickness map provides a new four-fold grouping of mesothermal gold-tungsten deposits in the Otago Schist.

The provisional structural thickness map is a simple and practical tool for interpolating and extrapolating point data in the Otago Schist. In combination with strain measurements and thermochronological data the map offers the potential for significant insights into the magnitude and timing of three-dimensional Otago Schist strain and exhumation. Methods similar to those described in this paper could also be applied to other metamorphic belts.

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