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Deformation processes in an accretionary prism: a study from the Torlesse terrane of New Zealand

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Abstract—The style of deformation observed in rocks of the Torlesse (Pahau) terrane, exposed in the Aorangi Range of the North Island, records accretion of thick trench fill by offscraping at the toe of a growing accretionary prism during the early Cretaceous. The relatively coherent nature of the Aorangi Range rocks enables detailed study of the deformation processes produced by offscraping and subsequently within the prism, and many of the structures observed in these rocks are consistent with those described from both modern accreting margins and other ancient accretionary terranes.

Overprinting relationships indicate three phases of folding and multiple faulting events. Early deformation involved large-scale sheath-like folding oblique to the overall trend of the margin, and development of an anastomosing axial-planar cleavage. Folding of the sediments promoted dewatering; the subsequent disruption of strata, by shearing parallel to bedding and low-angle to bedding faulting, records the transition to more brittle responses to the deformation. The most widespread folding phase (D_2) produced numerous upright, typically isoclinal folds, with local development of an axial-planar S_2 cleavage in macroscopic and some mesascopic fold hinges. The variable plunge of the fold axes to the NNE and SSW within the axial surface indicates progressive rotation of the fold axes after formation. Mesozoic strike-slip faulting most likely produced the open E–W-trending folds and warps of the third folding phase (D_3), in bedding already rotated to moderate dips. Faults which overprint the Mesozoic deformation, were formed in response to renewed subduction along the eastern coast of the North Island during the Cenozoic.

INTRODUCTION

MARINE geophysical surveys and deep sea drilling across modern convergent margins, together with studies of ancient onshore accretionary terranes, and theoretical and experimental modelling, have demonstrated the extreme variability and complexity of deformational processes which occur as a consequence of subduction and accretion (Byrne 1982, Moore *et al.* 1985). The early models of Seely *et al.* (1974) and Karig & Sharman (1975) proposed that accretionary prisms grew outward by offscraping trench sediments and incorporating them into the toe of the prism; a process known as 'frontal accretion' or 'offscraping'. On seismic profiles across modern convergent margins, offscraping is indicated by the presence of folds and imbricate thrusts (e.g. Moore & Karig 1976, White & Louden 1982, Moore *et al.* 1986). More recently accretion by 'underplating' has been proposed, whereby sediment is carried down and accreted to the underside of the prism, and this process has been inferred in modern prisms where the growth of the prism exceeds the net amount of sediment accreted at the toe (Watkins *et al.* 1981, Walcott 1987). Underplating is likely to proceed through the formation of thrust fault duplexes (Boyer & Elliott 1982, Silver *et al.* 1985), and duplexes have been interpreted in the deeper parts of some accretionary prisms on seismic profiles (Leggett *et al.* 1985, Sample & Moore 1987). At some modern convergent margins, both mechanisms appear to operate, simultaneously widening and thickening the prism (Leggett *et al.* 1985, Davey *et al.* 1986).

The complexly deformed Torlesse terrane of New Zealand is the largest of several subparallel late Paleozoic–Mesozoic terranes which record more or less continuous convergence at the New Zealand margin of Gondwana from the Permian through to the Mid-Cretaceous (Bishop *et al.* 1983). The Torlesse terrane consists predominantly of quartzo-feldspathic sedimentary rocks deposited by sediment gravity flows (MacKinnon 1983). Basic volcanic rocks which are often associated with coloured argillite, chert and limestone, form a minor but conspicuous component (Bradshaw 1972, Spörli 1978). Various workers have proposed that the complex deformation and low-grade metamorphism exhibited by Torlesse rocks occurred during their incorporation into an accretionary prism (Spörli 1978, MacKinnon 1983). The Torlesse terrane has been divided into the Rakaia (Permian to late Triassic) and Pahau (latest Jurassic to early Cretaceous) terranes by Bishop *et al.* (1983), and although many detailed structural studies have been undertaken in these rocks, regional-scale development and juxtaposition of the two terranes remains open to interpretation.

The rocks described in this study are exposed in the western Aorangi Range in the southernmost part of the North Island (Fig. 1). They are latest Jurassic to early Cretaceous in age (George 1988) and therefore belong

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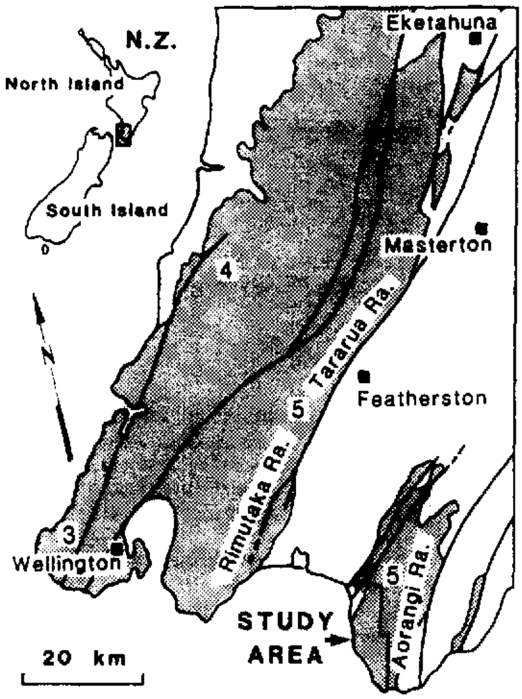

Fig. 1. Distribution of the Torlesse terrane (shaded) in the lower North Island of New Zealand, and location of the Aorangi Range. Fossils define broad age zones; 3 = late Triassic; 4 = Upper late Triassic; and 5 = late Jurassic–early Cretaceous (after Speden 1976, Foley *et al.* 1986).

to the Pahau terrane. The dominant rock types are interbedded turbiditic greywackes and argillites, with minor conglomerate, metabasite, coloured argillite, chert and melange. Multiple shortening and extensional events have produced the complex deformation observed in these rocks, however, the existence of relatively coherent sequences in the Aorangi Range makes them useful rocks in which to investigate deformational processes. This study attempts to provide a model for the deformation of Pahau rocks in the Aorangi Range within an accretionary prism framework.

Folds are well developed within the Aorangi Range rocks, and this style of deformation, by comparison with both modern and ancient convergent margins, is considered here to reflect thick sedimentation at a margin undergoing only slow to moderate (2–5 cm y^{-1}) rates of convergence (Moore & Karig 1976, Leggett *et al.* 1982, Schweller & Kulm 1982).

THE MECHANISM OF ACCRETION OF AORANGI RANGE ROCKS

Numerous structural studies in other ancient accretionary terranes around the world have shown that the sorts of structures interpreted on seismic profiles as evidence for offscraping and/or underplating are often preserved in the ancient terranes. Evidence for offscraping includes the preservation of relatively coherent rock sequences separated by high strain zones (e.g. the New England Fold Belt, Cawood 1982; and the Southern Uplands of Scotland, McKerrow *et al.* 1977, Leggett & Casey 1982), and/or the occurrence of trench slope basin deposits which indicate that the adjacent accreted material resided in the upper parts of the prism (Moore & Allwardt 1980, Byrne *et al.* 1987, Hibbard & Karig 1987). The development of thrust fault duplexes and pervasive shearing and stratal disruption, have led workers to propose accretion by underplating in some accretionary terranes (Sample & Fisher 1986, van der Pluijm 1988, Mackenzie *et al.* 1987, Sample & Moore 1987). Not surprisingly, both mechanisms of accretion have been recognized at different localities within the same terrane (e.g. the Franciscan Complex, Cloos 1988; and on Kodiak Island, Byrne *et al.* 1987).

Several features indicate that the Aorangi Range rocks were accreted by offscraping, although underplated rocks may reside at depth: (1) the recognition of relatively coherent rocks sequences separated by more highly sheared zones, which probably correspond to the original thrust faults produced during offscraping and subsequently rotated to near vertical; (2) the development of early folds prior to widespread stratal disruption; and (3) the preservation of a trench slope basin deposit within the accreted rocks (George 1988, in press). Relatively shallow levels within the prism are also indicated by the low prehnite–pumpellyite grade of metamorphism ($T < 300°C$; Liou *et al.* 1985). The absence of lawsonite, found in older Torlesse rocks in the North Island (George & Grapes 1987) indicates pressures less than 3 kb (Liou 1971), providing further evidence that these rocks were offscraped rather than underplated at depth.

DESCRIPTION OF STRUCTURES

Disruption of bedding

Bedding (S_0) in general trends NNE–SSW to NE–SW and is steeply dipping to vertical. Bedding-parallel shear is ubiquitous, and is preferentially concentrated in the argillite layers, particularly at the argillite–sandstone boundaries. It is responsible for the widespread destruction of grading and primary sedimentary structures (current marks, loading features and laminations) in the turbidites. Disruption of bedding was accomplished through movement on faults at low angles to bedding (<45°) accompanied by bedding-parallel shear. Low-angle and less common high-angle normal faulting is responsible for extension (or apparent thinning) of sandstone beds and produces a boudinage-like fabric (Fig. 2a). Individual lozenges typically have wedge-shaped terminations and rotation of the lozenges produces a new bed geometry with ragged top and base. Low-angle reverse faulting causes shortening (or apparent thickening) of sandstone beds (Fig. 2b). Field observations indicate that much of this low-angle faulting may have occurred in conjugate sets, with one set extending beds along normal faults and the other contracting beds along reverse faults (Fig. 2c). However, no systematic strain pattern could be discerned throughout the area.

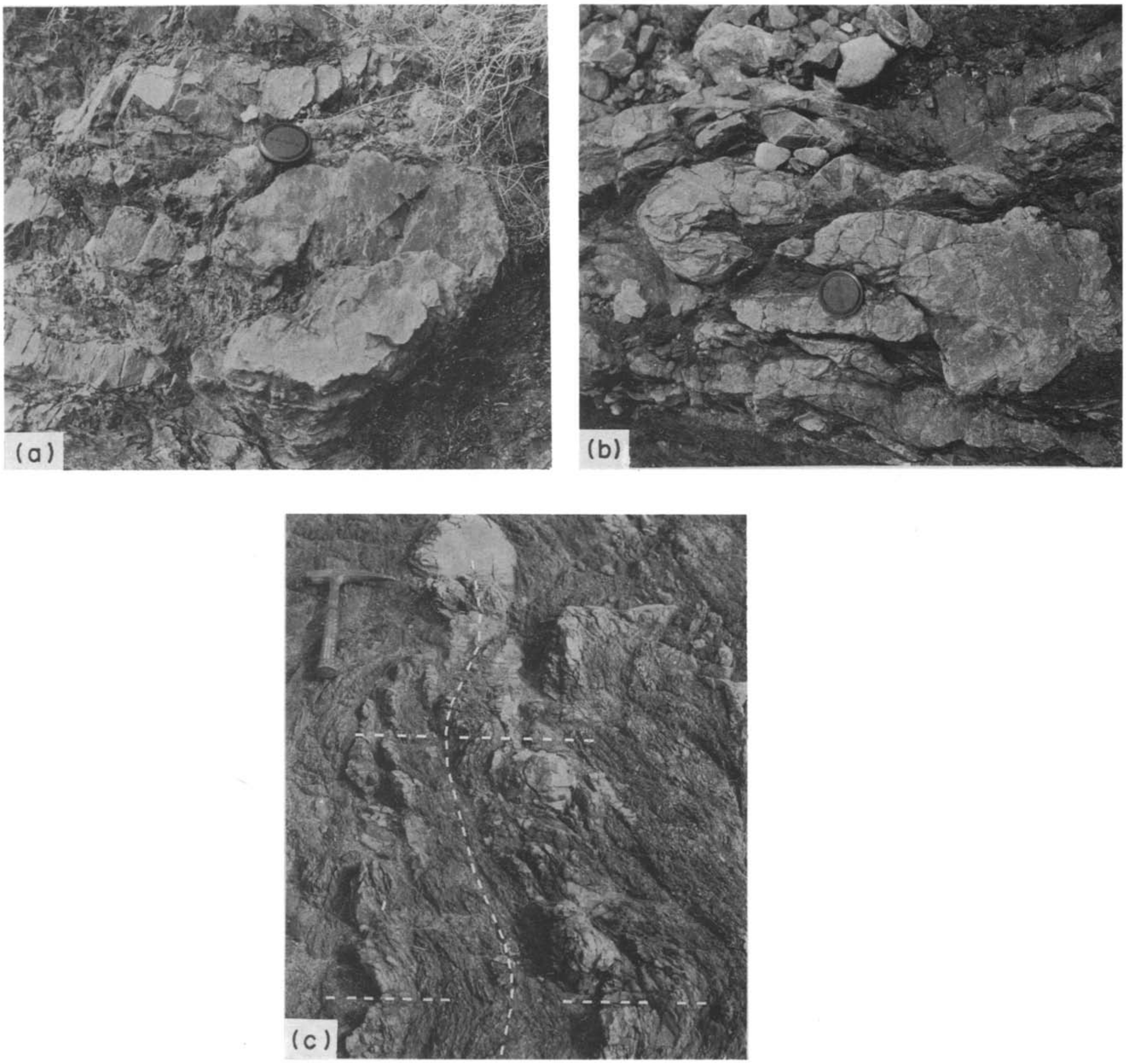

Fig. 3. Mesoscopic F_1 and F_3 fold shapes. (a) & (b) Rootless, steeply plunging, isoclinal F_1 folds in sandstone beds featuring thickened hinges and limbs disrupted by low-angle faults. Lens cap 5 cm. (c) Near-vertical isoclinal F_1 folds with N–S-striking axial surfaces (parallel to hammer handle) refolded by gentle F_3 folds with E–W-striking axial surfaces. Note thickened sandstone hinges and folded S_1 cleavage in the argillite. Hammer 35 cm long.

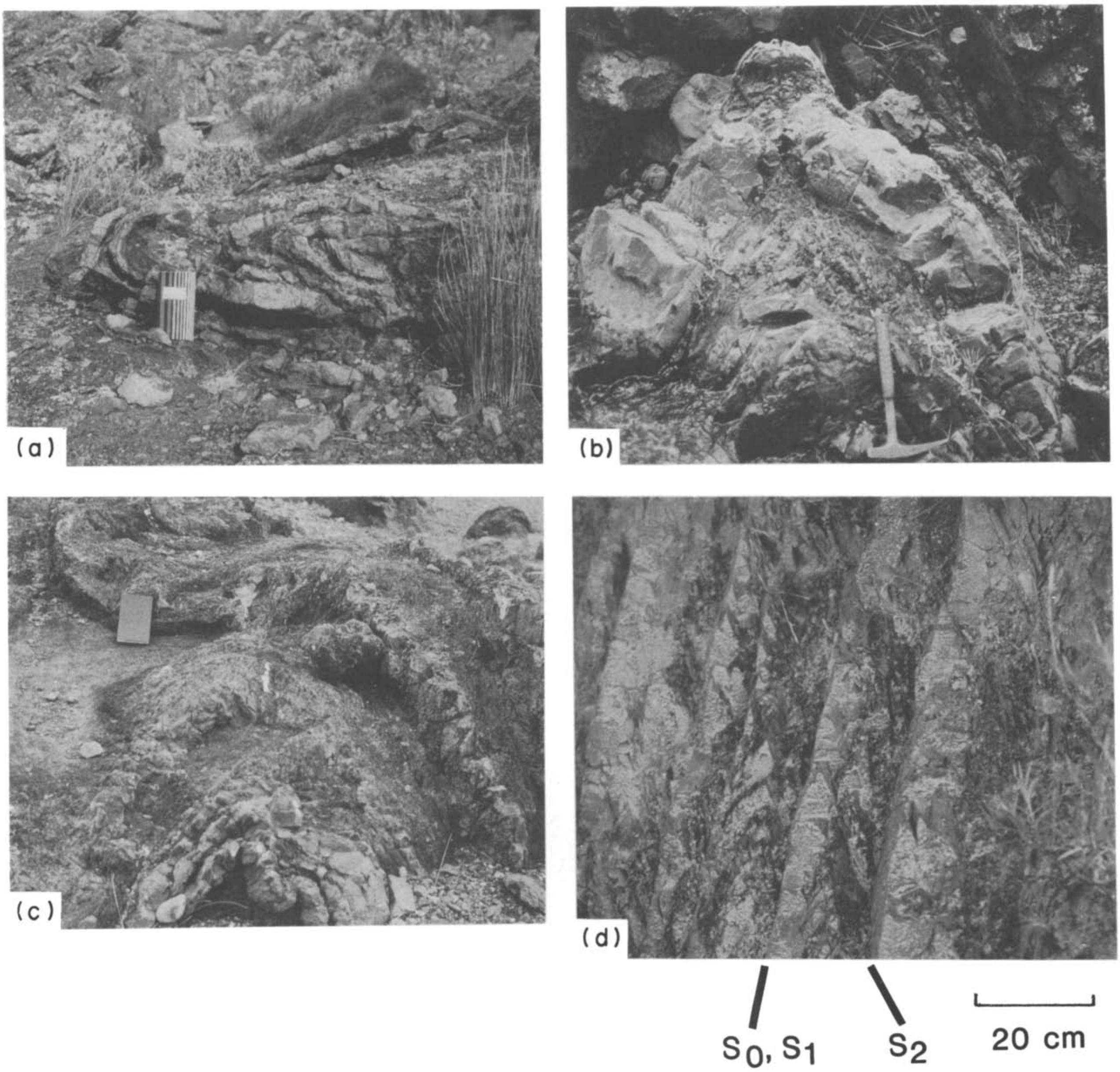

Fig. 4. Mesoscopic F_2 fold shapes and S_2 cleavage. (a) Gently plunging isoclinal fold in thinly bedded turbidites. Notebook 17 cm; (b) steeply plunging tight fold with an angular hinge and weakly developed axial planar cleavage in the argillite beds. Hammer 35 cm; (c) gently plunging, upward-facing asymmetric fold pair with round hinges. Notebook 20 cm; (d) locally developed planar to anastomosing spaced S_2 cleavage overprinting overturned thinly bedded turbidites (S_0) and bedding parallel S_1 cleavage. West is to the right.

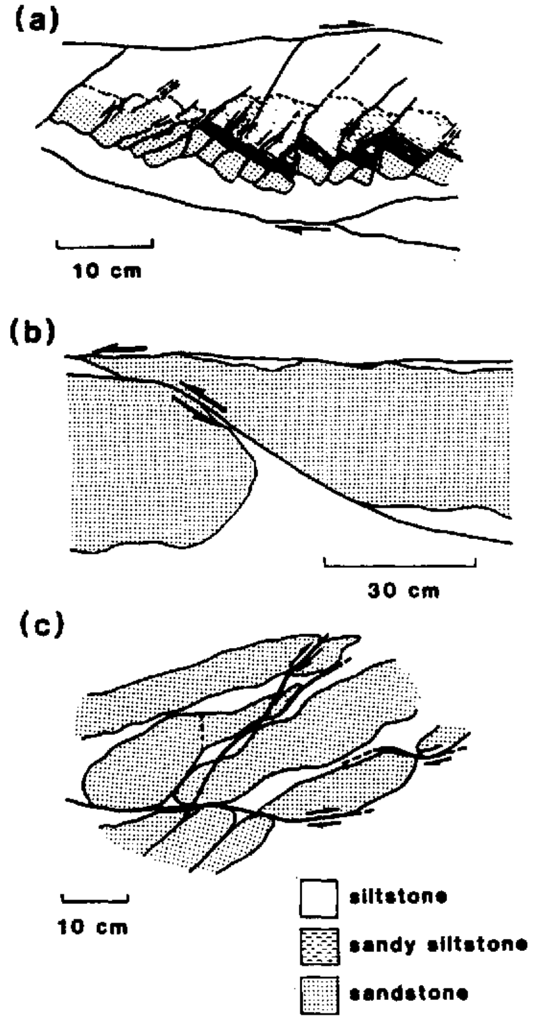

Fig. 2. (a) Apparent thinning of a sandstone bed by normal faulting at high angles to bedding and bedding-parallel shear indicating a dextral shear sense. Rotation of the blocks is clearly shown by the laminations in the sandstone. (b) Apparent thickening of a sandstone bed by low-angle reverse faulting. (c) Development of conjugate low-angle faults with opposite senses of movement.

A continuum from least disrupted through to highly disrupted bedding can be recognized. *Least disrupted* sequences are limited in extent, and although they have suffered some bedding-parallel shear, younging directions can be determined and mesoscopic folds recognized relatively easily. Most of the bedding in the area is *moderately disrupted* and it is often difficult to determine younging directions. Bedding is attenuated and broken into discrete blocks, but bedding attitudes are essentially preserved. Isolated hinges of mesoscopic folds may be difficult to recognize as such, and without younging criteria, folds may not be discernible in the stratigraphy. *Highly disrupted* sequences consist of bedding which is almost totally dismembered and unequivocal younging or fold evidence is rarely found. In other accretionary prism terranes, these sequences have been referred to as "broken formation" (Hsu 1974), "tectonic melange" (Bachman 1982, Korsch 1982, Byrne 1984) and "sandstone-rich melange" (Underwood 1984). In the western Aorangi Range, highly disrupted sequences occur in relatively narrow NNE-striking zones which separate the more coherent packets of strata and often correspond to known fault traces which are described below.

Melange

Highly disrupted sequences which are considered to be extremely fragmented bedding, are here separated from melange. The term 'melange' has been used by many workers to describe units which consist of blocks and clasts in a finer-grained matrix, which formed by different mechanisms (Raymond & Terranova 1984), possibly in different parts and at different times in accretionary prisms (Aalto 1981, Cowan 1985, Moore *et al.* 1985). Melange is not common in the western Aorangi Range, accounting for only 5% of the exposed rock, and most of the occurrences of greywacke, metabasite and chert blocks in argillite matrix are considered to have a sediment gravity flow origin. One melange which is described below, is interpreted to have been diapirically emplaced.

Mesoscopic folds

Mesoscopic folds are common in the area, and from overprinting relationships, three generations are recognized, termed F_1, F_2 and F_3. F_1 folds are all isoclinal in shape (Fig. 3), and are typically vertical or near-vertical and less commonly reclined (Fig. 5a). Folded sandstone layers typically show marked thickening in the hinges, and limbs are invariably disrupted by low-angle and high-angle to bedding faults (Fig. 3). A widespread anastomosing S_1 cleavage is inferred to have formed during this early folding event, and is everywhere parallel or sub-parallel to bedding. F_2 mesoscopic folds are the most common fold generation and are recognized because they fold the pre-existing S_1 cleavage. Fold shapes are predominantly isoclinal to close, but open to gentle folds also occur (Fig. 4). F_2 folds are highly variable, with sub-horizontal to steeply plunging axes to the SSW or NNE. Axial surfaces typically strike NNE–SSW and are steep to upright (Fig. 5b). A spaced planar to anastomosing axial-plane cleavage occurs in the hinges of some F_2 mesoscopic folds. F_3 mesoscopic folds also fold pre-existing foliations and are close to gentle with round hinges (Fig. 3). The orientation of these folds depends on pre-existing bedding attitudes but most fold axes plunge steeply to the east or west within axial surfaces which strike E–W or NW–SE and are steeply inclined to upright (Fig. 5c). The southern part of the area has been intruded by doleritic and camptonitic dykes and sills of late Cretaceous age (90–100 Ma, Challis 1966) which do not appear to be folded, and therefore all folding is considered to have occurred during the Mesozoic.

Macroscopic folds

The occurrence of upward- and downward-facing mesoscopic F_2 folds (using the fold facing criteria of

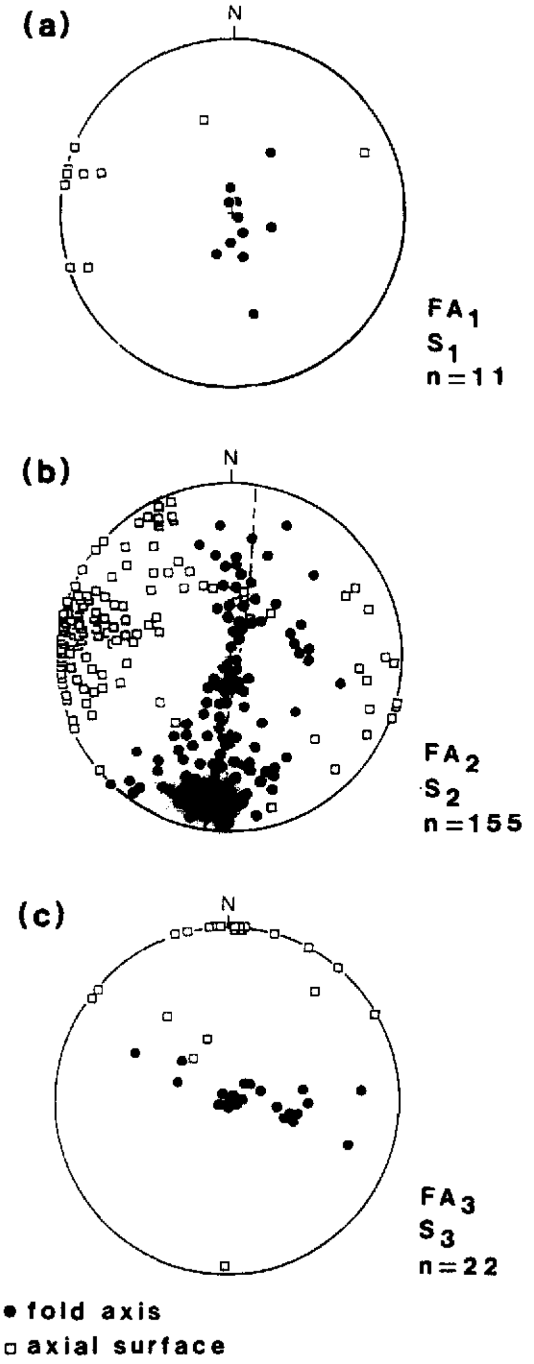

Fig. 5. Equal-area plots of fold axes and poles to axial surfaces from each folding phase. (a) F_1 folds; (b) F_2 folds; and (c) F_3 folds.

Borradaile 1976), indicates the presence of earlier-formed F_1 macroscopic folds. The distribution of the mesoscopic folds in areas where stratigraphic younging is well preserved allows definition of macroscopic S_1 surfaces. The best defined and most continuous sequence where a form-surface interpretation can be made is in the lowermost part of Kawakawa Stream (Fig. 6), where wavelengths of 1.5–2 km are indicated. Note that the exposures are best in the stream bed, and that no data exists to constrain the location of the fold hinges, thus the fold closures shown indicate direction of closure only. In addition, exposure is not continuous enough along strike to allow recognition of large-scale interference patterns. Macroscopic F_2 folds can also be recognized in some least disrupted areas. In the lower part of Hurupi Stream, macroscopic F_2 folds can be mapped by the distribution of lower-order F_2 folds and reversals in younging, indicating wavelengths of 200–300 m approximately (Fig. 7). A planar to anastomosing spaced S_2 cleavage is developed in the hinge regions of these folds, and clearly overprints S_1 (Fig. 4d). Open macroscopic F_3 folds are best developed in the greywacke in the southernmost part of the area, where they are responsible for anomalous E–W-striking bedding, and clearly fold mesoscopic and macroscopic S_2 surfaces.

Mesoscopic faults

Mesoscopic faults and shear zones are very common and variable in orientation, although NNE–NE-striking faults (of which there are several generations) are the most common (Fig. 8). Complex overprinting relationships indicate that mesoscopic faulting occurred throughout the Cretaceous deformational history of the greywacke. Early low- and high-angle to bedding faulting which produced the widespread stratal disruption, is overprinted by several generations of high-angle faults. Offsetting of S_0, S_1, S_2 and F_2 fold limbs indicates that much of this faulting post-dates D_2 folding. Some faults which have been folded during D_3 or intruded along their planes by late Cretaceous dykes are clearly Cretaceous in age. However, the renewal of subduction along the eastern coast of the North Island about 25 Ma ago has resulted in faulting throughout the Aorangi Range (in response to underthrusting beneath the range), so that precise age assignment is difficult and many post-D_2 faults may be late Cretaceous or late Cenozoic in age.

Joints and veins

Joints are ubiquitous in sandstone beds. Their complex, highly variable nature precludes systematic study. Joints oriented normal to bedding are common, and are considered to form early in the structural history as they are frequently deformed by F_2 folds. Closely spaced, quartz filled fractures (up to 1 cm wide) occasionally occur in the thinned 'necks' of sandstone beds. These fractures indicate tectonic stretching of the more competent beds by 'classical' boudinage (Rast 1956), as opposed to the development of lozenges by low-angle faulting and bedding plane shear. Veins are the most obvious field evidence for metamorphism of the greywacke. Calcite and quartz are the major vein-forming minerals in the greywacke and chert, whereas in the metabasaltic and coloured argillaceous rocks, calcite with heterogeneous Fe–Al rich epidote, prehnite and pumpellyite form the most common assemblages. The variably-oriented veins are commonly of mm-scale width, but range up to 0.15 m, and in zones of intense veining, may almost entirely replace the host greywacke or metabasite. The highly deformed nature of small

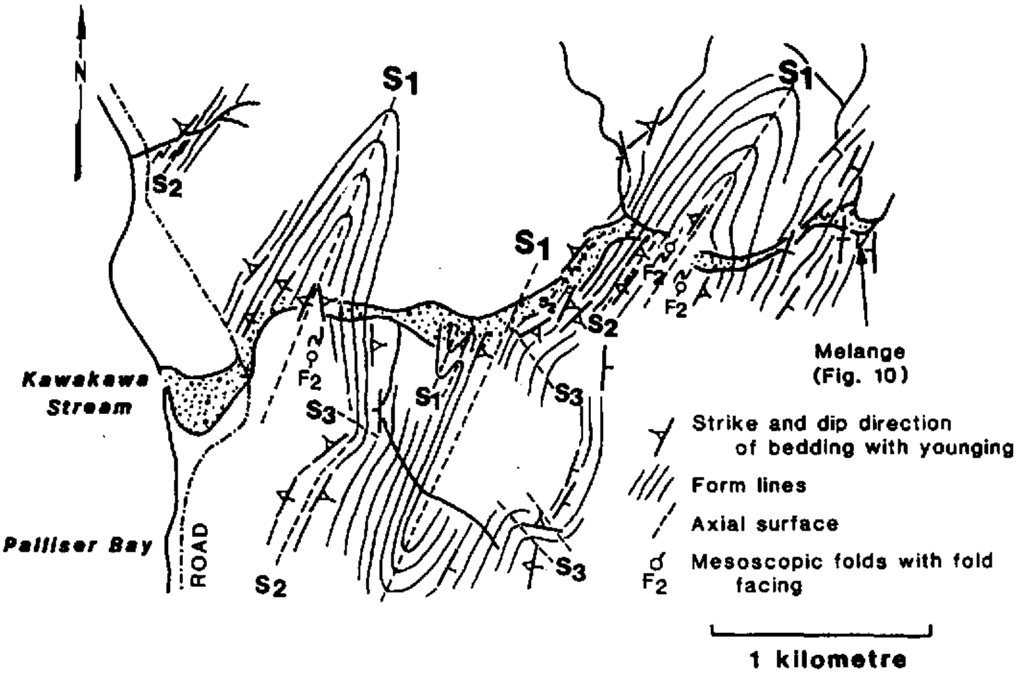

Fig. 6. Form–surface map illustrating upward-facing macroscopic F_1 folds using structural data from the lowermost part of Kawakawa Stream (location shown on Fig. 9). Stream bed shown by gravel pattern. Downward-facing F_2 folds occur on the east younging limbs of the macroscopic F_1 folds. F_1 fold hinges are drawn to show direction of closure only. S_1 traces are shown as straight lines for simplicity, although axial surface for the central syncline is more than likely refolded about F_3 axes. Mesoscopic F_2 folds are exaggerated for clarity.

veins subparallel to bedding suggests a relatively early emplacement (prior to D_2) in some sequences.

Macroscopic faults

Two major fault orientations are evident in the western Aorangi Range, one striking NNE–SSW and the other striking NE–SW. Bates (1967) and Kingma (1967) mapped several major subvertical NNE-striking faults in the western Aorangi Range, and additional NNE-striking faults have been mapped in the area during this study (Fig. 9). These faults are marked by zones of highly disrupted bedding or abrupt changes in structural style and bedding characteristics. These faults divide the area into 1–5 km elongate blocks which probably represent the original bounding faults of the thrust packets subsequently rotated to subvertical. Some of the NNE-striking faults have been active in the Cenozoic, such as the Cape Palliser Fault and the Mangatoetoe Fault (Fig. 9) (Kingma 1967, Stevens 1974). Ghani (1978) documented several NE-striking faults which offset the Quaternary coastal marine terraces with vertical displacements up to 35 m. These faults cross-cut and are therefore younger than the dominant NNE-striking

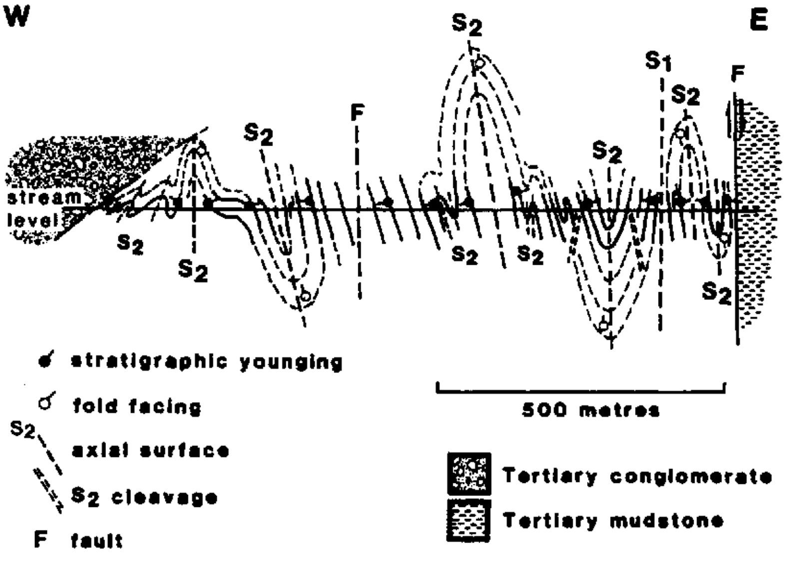

Fig. 7. Schematic cross-section showing macroscopic F_2 folds developed in the lowermost part of Hurupi Stream (location shown on Fig. 9). Mesoscopic structures are exaggerated for clarity.

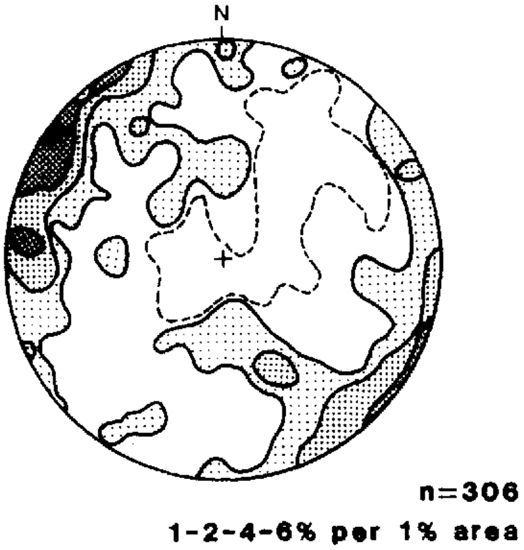

Fig. 8. Equal-area plot of poles to mesoscopic faults and shear zones showing the variable orientations, and common NNE–NE-striking, steeply dipping orientation. Dashed line = extent of data.

faults, and additional lineaments mapped from aerial photographs have a similar orientation (Fig. 9). Earthquake focal mechanisms in the area are recorded in the subducting plate which is located only 11 km below Cape Palliser whereas the Aorangi Range on the overriding plate is seismically quiet (Robinson 1986). Recent scarps in the range indicate the predominance of dip-slip movement.

SUMMARY OF TECTONIC EVENTS

Overprinting relationships between structural features in the western Aorangi Range indicate the following relative order of tectonic events.

(1) Early deformation (D_1) involving folding (F_1),

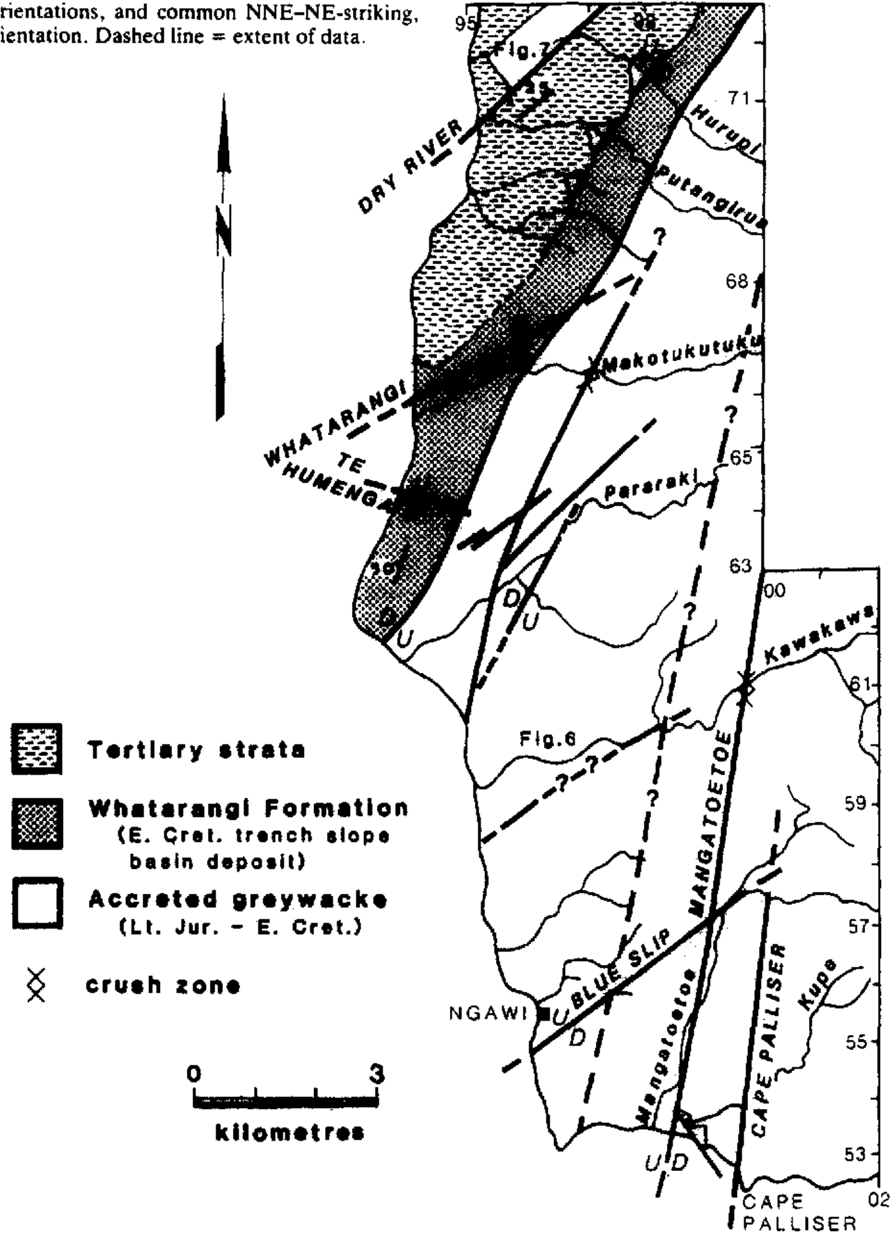

Fig. 9. Distribution of macroscopic faults (shown by heavy lines) in the western Aorangi Range. Fault names are shown in capitals and senses of movement indicated where known. Average orientations for Tertiary strata and Whatarangi Formation are also shown.

production of widespread cleavage (S_1), and disruption of bedding by parallel shear and low- and high-angle to bedding faults. F_1 folds now appear steeply plunging with bedding-parallel steeply inclined axial surfaces.

(2) Widespread F_2 folding characterizes the second deformation (D_2), and was accompanied by continued faulting and stratal disruption. F_2 fold axes plunge variably to the NNE or SSE, and their distribution parallels the dominant axial surface orientation, providing evidence for the progressive nature of this deformation.

(3) D_3 produced folding (F_3) superimposed on bedding already rotated to moderate dips. This folding is possibly related to strike-slip faulting during the Cretaceous because the late Cretaceous dykes and sills do not appear to be folded.

(4) Continued faulting and rotation of the basement related to recommencement of underthrusting 25 Ma ago along the present-day plate boundary off the east coast of the North Island. In the Aorangi Range, overlying Tertiary sedimentary rocks record up to 45° tilt since late Miocene.

DIAPIRICALLY-EMPLACED MELANGE

The melange is only exposed on the true left bank of Kawakawa Stream (Fig. 10a), and does not appear to extend laterally north or south. Irregular blocks of greywacke, green metabasite and green, red and grey chert, which range in size from 1 to 70 cm, lie in a sheared black argillite matrix. The downstream (western) contact is concordant with the adjacent thickly bedded turbidites but is very sheared and veined with calcite. The upstream (eastern) contact is concordant with thinly bedded greywacke, and immediately adjacent to this contact, the melange appears to contain a higher proportion of small greywacke clasts. Similar greywacke clasts are predominant along the downstream contact but this fabric was most likely produced by shearing at this margin. Relict banding defined by elongate blocks of greywacke and metabasite, and irregular calcite veins have similar attitudes to bedding on each side of the melange (NNE–SSW to N–S; Fig. 10a). However, they are strongly overprinted by an anastomosing shear foliation which strikes NE–SW and dips steeply to the SE, and tends to wrap around the blocks (Fig. 10b). In thin section, the shear surfaces are narrow zones of dark semi-opaque clays and insoluble material containing very small detrital grains.

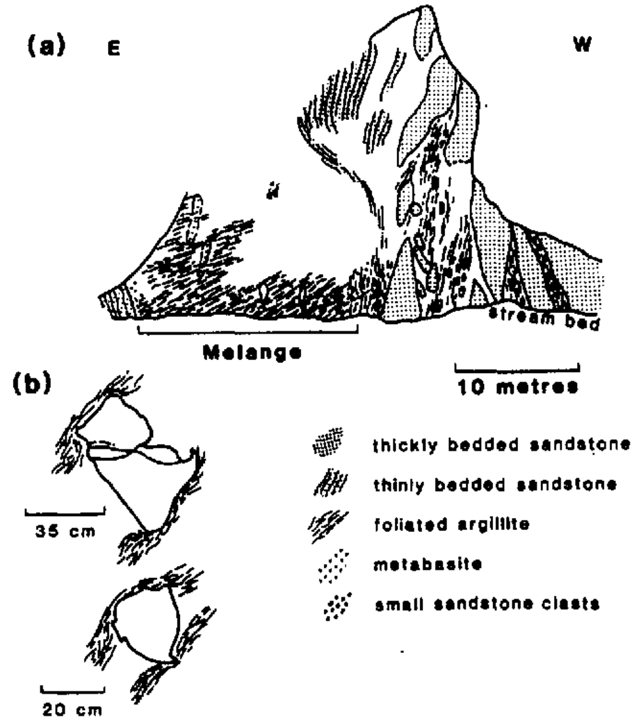

Fig. 10. (a) Illustration from photographs and field sketches of the melange exposed in the true left bank of Kawakawa Stream (location shown on Fig. 6). Thinly bedded turbidites are exposed in the bank above the melange. Note the relict fabric defined by elongate blocks in the melange and the overprinting shear foliation. (b) Illustrations from photographs of two chert blocks within the melange showing partly sub-rounded shape with re-entrants. The foliation in the argillite tends to wrap around the blocks.

The origin of the melange could be sedimentary, tectonic or diapiric, as all are known from accretionary prism terranes, but the tectonic overprint makes interpretation difficult. Although a sedimentary origin (by gravity flow) or tectonic disruption during faulting cannot be ruled out, a diapiric origin (using the criteria of Barber *et al.* 1986) is possibly the best explanation. Some of the criteria are difficult to apply because of the tectonic overprint (e.g. scaly argillite matrix), however four features of the melange are consistent with the diapiric melanges described by Barber *et al.* (1986):

(1) the outcrop has a lensoidal shape, with locally concordant boundaries;

(2) the blocks have an irregular shape, in part angular, in part sub-rounded featuring re-entrants (Fig. 10b);

(3) abundant argillite clearly supports the clasts and blocks;

(4) melange is located at a major structural break (likely thrust packet boundary) between a well bedded, weakly to moderately disrupted turbidite sequence downstream, and a moderately to highly disrupted sequence in the upper part of the stream. The location is consistent with the proposal by Barber *et al.* (1986) that the diapirs are localized along thrusts or steep faults. The increase in the number of greywacke clasts along the margin is possibly consistent with an intrusive origin.

The precise timing of diapiric emplacement of the melange is unknown, but presumably occurred early in the deformation, providing an escape route for the overpressured muds. In addition, the intersection of the relict banding in the melange and the overprinting shear foliation plunges moderately steeply to the SSW, consistent with its formation during D_2.

COMPARISONS WITH OTHER NORTH ISLAND TORLESSE STUDIES

In recent years, several workers have made detailed structural studies of areas in the lower and central North

Island (e.g. Spörli & Barter 1973, Spörli & Bell 1976, Rattenbury 1986, Korsch & Morris 1987). Compared to the structure of the western Aorangi Range, several broad similarities in structural style emerge.

(1) An early generation of folding which is now typically isoclinal and may be steeply plunging.

(2) Early disruption of bedding and melange formation, either before, during or after the earliest recognized phase of folding.

(3) A second generation of isoclinal to open, usually asymmetric, upright to steeply inclined folds. Although in some areas these folds are dominantly sub-horizontal (Spörli 1978), the western Aorangi Range folds range from sub-horizontal to sub-vertical.

(4) The last generation of folding is typically steeply plunging, open to gentle, upright and asymmetric.

MESOZOIC DEFORMATION OF AORANGI RANGE TORLESSE

The following model is proposed to explain the deformation of the Torlesse rocks exposed in the western Aorangi Range during accretion and subsequently within the prism, and is presented diagramatically in Fig. 11.

Earliest deformation (D_1)

The early folding, faulting and stratal disruption equates well with the style documented from the toe regions of modern accretionary prisms (Moore & Karig 1976, White 1982, Leggett *et al.* 1985, McCarthy & Scholl 1985, Lewis *et al.* 1988). The earliest folding probably occurred before the sediments had undergone significant dewatering and lithification, and while high fluid pressures existed (Brown & Westbrook 1987, Davis & von Huene 1987). The typical appearance of F_1 mesoscopic folds in the study area with thickened hinges and sheared limbs, or as rootless folds with both limbs sheared out, indicates that much of the early stratal disruption followed folding. Folding presumably promoted dewatering (e.g. Fowler *et al.* 1985), with the response to the deformation becoming more brittle as the mechanical properties of the sediment changed during lithification. Underwood (1984) has suggested that the expulsion of water may also contribute to stratal disruption.

In the basic imbricate-thrust model (Seely *et al.* 1974, Karig & Sharman 1975) early folds are depicted as recumbent, with sub-horizontal axes parallel to the trench. As accretion continues, the folds (and accompanying thrust faults) are rotated to a near upright position without significant reorientation of the fold axes. Modern studies frequently document fold ridges and thrusts trending more or less parallel to the trench (White 1982, Breen *et al.* 1986), although these folds may be variably plunging (Leggett *et al.* 1985). In some ancient terranes, early sub-horizontal, upright to steeply inclined folds are observed (Moore 1973, Byrne 1982, Leggett & Casey 1982). The early folds in the Aorangi Range are now steeply plunging (Fig. 11a), and cannot be explained by simple refolding of originally margin-parallel recumbent folds. If bedding is simply rotated back to horizontal (about the average NNE-strike direction) as suggested by Spörli (1978), the early sub-horizontally formed fold axes have a WNW–ESE trend (Fig. 11b). Spörli (1978) suggested that these early folds record the oblique vector of convergence and he described several other studies in the North Island which record oblique trends. Another possible explanation which is favoured here, is that the F_1 folds developed as sheath folds during progressive rotation of fold hinges. Quinquis *et al.* (1978) considered that sheath folds could develop in deep parts of accretionary prisms, but more recently, Hibbard & Karig (1987) describe sheath-like folds from the structurally shallow, high-strain environment at or near the toe of the prism. It is proposed that the hinges of F_1 folds preserved in the Aorangi Range developed essentially parallel to the margin, but underwent rotation within the axial plane during offscraping.

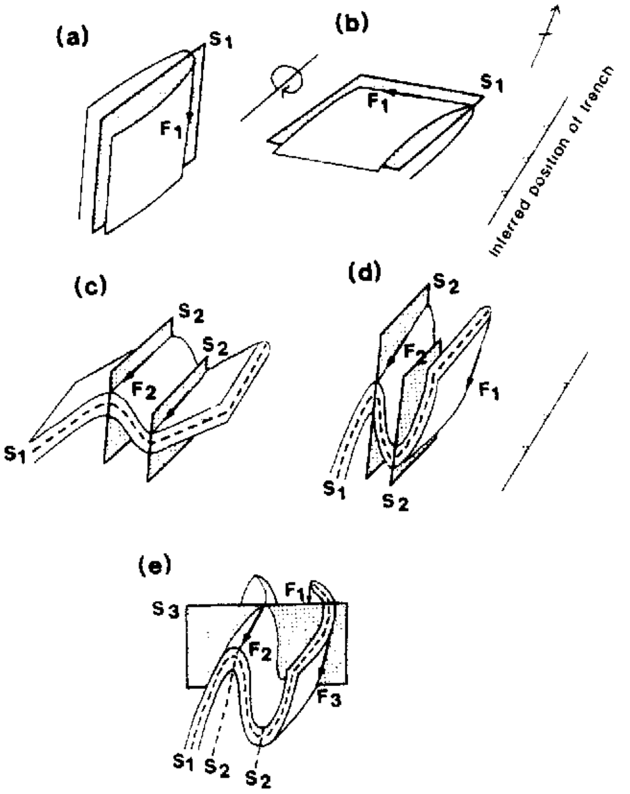

Fig. 11. Schematic diagrams illustrating the fold history of the Aorangi Range Torlesse rocks. (a) Present-day orientation of F_1 folds. (b) Back rotation of the steeply plunging F_1 folds about the average strike direction (NNE) restores folds to an initial sub-horizontal, gently inclined attitude with axes which trend WNW (i.e. removing the effects of arcward rotation of thrust packets). (c) As the F_1 folds within the older packets begin to rotate arcward, and NNE–SSW-trending F_2 folds are developed in bedding which probably dips no more than 20–30°. (d) As D_2 progresses, F_2 fold axes are rotated to steeper plunges and folds tighten. The refolded F_1 axes become increasingly steep and S_1 is brought into parallelism with S_2. (e) The 45° tilt on overlying Miocene strata and present near vertical bedding, implies that F_3 folding occurred when bedding was moderately dipping (no more than 45°). Folding is gentle about E–W-trending axes and E–W-striking axial surfaces.

Recent deep sea surveys of modern trenches reveal that bathymetric highs on the subducting plate (e.g. basement ridges or seamounts) which are in the trenches, can cause localized uplift and change the shape of the accretionary prism toe (Fryer and Hussong 1985, Brown & Westbrook 1987, Lallemand & Le Pichon 1987). These surveys also reveal that the seamounts are entirely or almost entirely subducted (Lallemand & Le Pichon 1987). Volcanic outcrops are common in many parts of the Pahau terrane and they represent fragments of bathymetric highs which were rafted into the trench during Cretaceous subduction. The effects on offscraping processes by the consumption of these highs may introduce local variations in the trends of major structures.

Widespread folding (D_2)

D_2 folding is the most widespread and best developed folding phase and most likely accompanied the main metamorphic phase. After early folding and accretion, the NNE–SSW-trending F_2 folds most likely developed in bedding dipping 20° or 30° to the west, after some back rotation of thrust packets (Fig. 11c). In modern prisms, early folded strata can be traced into seismically opaque deformation zones, which are located from 15 to 20 km (Leggett *et al.* 1985) up to 70 km (Fowler *et al.* 1985) from the toe of the prism. This is the most suitable site for the second folding phase seen in the Aorangi Range rocks.

F_2 fold axes are variably oriented along a NNE–SSW girdle, and mesoscopic folds are frequently incongruous with respect to their host structures. The girdle coincides with the dominant axial surface orientation of the folds and suggests that the deformation was progressive, whereby folds once formed, were flattened and rotated to steeper plunges (Borradaile 1972, Ramsay 1979), without significant stress field changes throughout the deformation (Ramsay & Sturt 1973). Progressive rotation of fold hinges has also been described from a number of accretionary prism terranes (Moore & Allwardt 1980, Bosworth & Vollmer 1981, Hibbard & Karig 1987, Mackenzie *et al.* 1987). Thus F_2 folds are inferred to have developed as open, sub-horizontal folds in moderately to gently dipping strata, which were subsequently rotated to steeper plunges within the prism (Fig. 11d). The superposition of F_2 folding on the earlier-formed F_1 folds produces the steeply plunging F_1 fold axes and brings S_1 into parallelism with S_2 (Figs. 11c & d). The occurence of sub-horizontal and girdled F_2 folds in different parts of the terrane in the North Island is best explained by some thrust packets having undergone greater amounts of strain, as suggested by Larue & Ueng (1985). Numerous post-F_2 faults observed in the area indicates that faulting was continuing after this folding phase.

Fault-related folding (D_3)

The last folding phase produced asymmetric folds in moderately dipping strata (no more than 45°; Fig. 11e). Spörli & Bell (1976) suggest that the folding was due to late faulting with a strike-slip component, and propose a late Mesozoic age, although Spörli (1978) suggests at least some of the folding may have occurred in Cenozoic time, due to the association of folds with active faults. The lack of folding of the late Cretaceous dykes in the western Aorangi Range supports a Mesozoic age for the formation of F_3 folds. Vergence of F_3 folds and sense of offset on post-F_2 faults is both dextral and sinistral, and is consistent with relatively late strike-slip faulting recorded from other accretionary prisms (Larue & Ueng 1985, van der Pluijm 1986, Sample & Moore 1987).

SUMMARY

The structural styles observed in the Torlesse rocks of the western Aorangi Range are similar in many respects to those which have been described from both modern prisms and other ancient accretionary terranes. Deformation principally by folding indicates an abundance of sediment and only slow to moderate rates of convergence. The development of folds, the coherent nature of rock sequences separated by highly disrupted (higher strain) zones, the low metamorphic grade ($T < 300°C$, $P < 3$ kb), and the presence of a trench slope basin deposit, tend to favour offscraping as the mechanism of accretion in the rocks presently exposed. The following history is proposed to explain the Mesozoic deformation observed in the western Aorangi Range.

(1) Early folding followed by stratal disruption records offscraping of trench turbidites and their incorporation into the toe of the accretionary prism. High strains caused progressive rotation of early fold hinges to orientations which were orthogonal to the trench. Folding promoted dewatering and lithification, and the subsequent disruption of strata by faults reflects the transition to more brittle responses to the deformation.

(2) Widespread folding within the accreted thrust packets arcward of the prism toe occurred along sub-horizontal NNE–SSW axes and accompanied the main metamorphic phase. Rotation of the fold axes to steep plunges records a progressive style of deformation within the prism.

(3) Development of E–W oriented, open folds in moderately dipping strata, in response to relatively late sinistral and dextral strike-slip faulting.

(4) Continued strike-slip and dip-slip faulting.

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