



Structural signature of sediment accretion in a Palaeozoic accretionary complex, southeastern Australia

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Abstract—Chaotic block-in-matrix melange, broken formation along high strain zones associated with large scale imbrication, early bedding-parallel cleavage, recumbent folds in turbidites, and structural complexity in cherts are key elements of a mid-Palaeozoic subduction complex in the eastern part of the Lachlan Fold Belt, southeastern Australia. The complex consists of an imbricated turbidite, chert and basalt sequence of mid-Cambrian to Late Ordovician age. Structural and biostratigraphic controls require a complexly imbricated sequence with reversals in younging seawards towards the inferred former trench/subduction zone, as in young subduction accretionary complexes such as the Kodiak accretionary complex in the Aleutians and the Shimanto complex of Japan. Subduction accretion or underplating in the Narooma accretionary complex is not typified by duplexing, but shows a strain-dependent transition from an “inland” belt of chevron-folding cut by reverse faults, to a coastal belt with an early bedding-parallel fabric, isoclinal-recumbent folding, poly-deformation and differentiated layering in quartz-rich turbiditic greywackes. Greywacke units show multiple cleavage fabrics formed in one folding event. Cherts below the turbidites show multiple folding events and zones of broken formation with intense veining and stylolitisation. The structurally lowest units, including deformed pillow basalts and block-in-matrix melange, show strong planar-linear fabrics. In the block-in-matrix melange, prolate-shaped pods of greywacke and chert are aligned sub-parallel to the bulk extension direction defined by mica pull-aparts and pressure shadows on pyrite within the mudstone matrix. Mica neocrystallisation and pressure solution are the dominant deformation mechanisms at the base of the complex. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Recognition of palaeo-subduction zones in ancient terrains has been linked to the presence of broken formation typical of modern accretionary complexes, melange with exotic blocks, and at deeper levels high pressure (blueschist) metamorphism (e.g. Leggett *et al.* 1982, Lash 1985, Cross *et al.* 1987, Hansen 1988, Fergusson *et al.* 1990). The position and delineation of former sites of subduction have often been controversial due to levels of exposure, the lack of preservation of key elements and the multitude of structural and stratigraphic forms of underthrust margins (Scholl *et al.* 1980, Leggett *et al.* 1982, von Huene 1984, Jarrard 1986). For example, sediment subduction at some modern subduction zones means an accretionary prism will not develop (Hilde 1983, von Huene 1986, von Huene & Scholl 1991). Oceanic crust and exotic pelagic sediments will not be present if offscraping has not occurred. In this case, the rocks at the toe of the complex will have been *in situ* prior to subduction, i.e. they belong to the upper plate and are autochthonous. Pelagic sediments and oceanic crust also may not be present if offscraping occurs within a thick pile of turbidites and does not reach down into the deeper levels of the stratigraphic section on the lower plate. Distinguishing between exotic or *in situ* turbidites may be very difficult, given that sandstone provenance can look very similar along a continental margin with active subduction. Whilst it is possible that exotic lithologies may be thrust deeply beneath the *in situ* sediments of the overriding plate, identification of such an underplated unit (or diagnostic blueschist facies metamorphism) will depend on the level of exposure. The presence of melange may

point to a subduction zone, but melange can also form in other environments (Cowan 1985, Lash 1985, Needham & MacKenzie 1988).

This paper highlights problems in the identification of a fossil subduction zone in the Palaeozoic Lachlan Fold Belt of eastern Australia. The paper investigates an imbricated turbidite, chert, basalt and melange sequence exposed along the southeastern coastline of New South Wales (Figs. 1 and 2). In this strongly deformed Palaeozoic succession, structural relationships suggest that an accretionary prism containing offscraped exotic lithologies has not developed or has not been preserved. Underplating has been identified, but the underplated units appear to be composed of sediment that was derived from the upper plate. The paper investigates the meso-scale structure and microstructure of intermediate level subduction fabrics within the macro-scale structural context of the fossil subduction zone and attempts to determine their origin and significance.

GEOLOGICAL SETTING

The Lachlan Fold Belt is a 700 km wide belt of deformed, deep marine sediments, mafic and shoshonitic volcanic rocks which forms part of the early to mid-Palaeozoic Tasman Orogenic Zone of eastern Australia. The dominant rock type is an Ordovician deep-marine turbidite succession which had original dimensions comparable to the Bengal fan (eg. Cas 1983, Powell 1984, Fergusson & Coney 1992a). This Ordovician fan is inferred to have been deposited in a passive margin setting (VandenBerg & Stewart 1992). However, the turbidite sequence is derived from an adjoining active

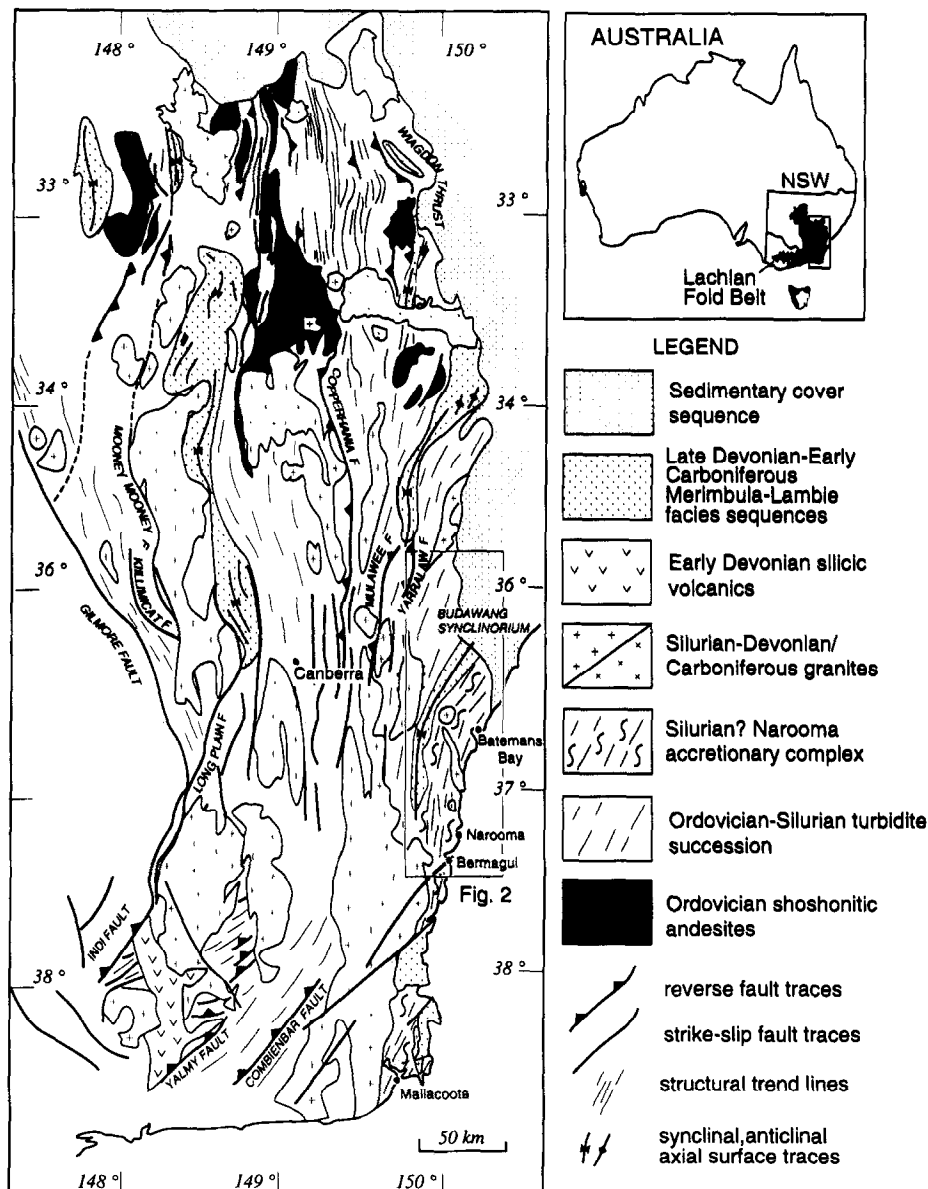


Fig. 1. Structural map of the eastern Lachlan Fold Belt, southeastern Australia showing major faults, structural form lines, granites, cover sequences and the extent of the Narooma accretionary complex. Inset shows position within the Lachlan Fold Belt (modified from Gray 1997).

orogenic belt (Delamerian-Ross Orogen), and is not the outer sedimentary prism of a rifted continental margin, as implied by a passive margin setting.

The Lachlan Fold Belt consists of three distinct parts, each with differences in lithology, metamorphic grade, structural history and geological evolution (Glen 1992, Gray 1997). The western and central parts are dominated by a turbidite succession consisting of quartz-rich sandstones and black shales, whereas the eastern belt (Fig. 1) consists of shoshonitic volcanics, mafic volcanoclastic rocks and limestone in the north, and quartz-rich turbidites and extensive black shale in the easternmost part (VandenBerg & Stewart 1992). The nature of the basement to the turbidite succession is controversial. In the eastern belt the oldest rocks observed are Ordovician shoshonitic volcanics and a Late Cambrian to Late Ordovician chert/turbidite sequence (Fig. 2), whereas in the western belt Cambrian mafic volcanics of oceanic

affinities underlie the quartz-rich turbidite succession.

Structurally, the eastern Lachlan Fold Belt consists of a fold-thrust zone (Fig. 3; A-A' and B-B') that formed in the mid-Silurian to mid-Devonian during a period of plate convergence between Gondwana and the palaeo-Pacific ocean (Fergusson & VandenBerg 1990). The fold-thrust zone was inferred to have an arc-frontal setting above a west-dipping subduction zone (Fergusson & Coney 1992b, fig 10). Rocks in the easternmost part are a typical ocean-floor sequence with basalts passing upwards through cherts to pelagic sedimentary rocks (Leitch & Scheibner 1987, Coney *et al.* 1990, Glen 1993). The sequence has been recognised as an accretionary complex on sedimentologic (Powell 1983), stratigraphic and palaeontologic grounds (Bischoff & Prendergast 1987), although this recognition has not gained general acceptance.

The intensely deformed turbidite and chert sequences

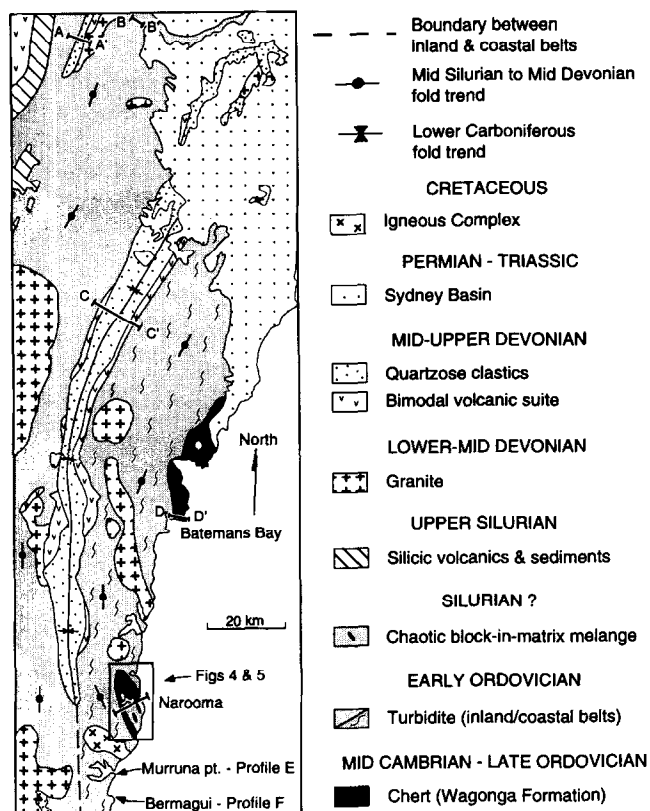


Fig. 2. Geological map of part of the Narooma Accretionary Complex showing 'inland' and 'coastal' structural belts (modified from NSW Geological Survey 1:250,000 Geological map sheets).

are overlain by mid to Late Devonian volcanics and clastics (Lambie and Merimbula facies) separated by a high-angle unconformity (Fig. 2). These lithologies indicate transition from a deep marine to a shallow marine/terrestrial setting in the Siluro-Devonian time period. Early Carboniferous deformation has resulted in these mid to Late Devonian sediments being folded into broad synclinal and anticlinal structures (Figs. 1 and 2; Budawang synclinorium, Fig. 3; profile C-C').

IMBRICATED ACCRETIONARY COMPLEX

The Narooma accretionary complex is defined as a westwards dipping, folded, imbricated succession (Figs. 3–5). The sequence from structurally highest to lowest includes turbidites, chert, pillow basalt and chaotic block-in-matrix melange (Fig. 6).

Turbidite sequence

Turbidite comprising greywacke and slate is the dominant sedimentary facies in the imbricate stack. The turbidite sequence may be subdivided into inland and coastal structural belts (Fig. 2), which approximately coincide with the inland and coastal facies of Powell (1983). The coastal belt has an early slaty cleavage at a low angle to bedding, contains early isoclinal-recumbent folds and localised polydeformation (Fig. 3; profiles E and F) (Williams 1971, 1972, Wilson *et al.* 1982, Powell

1983, Powell & Rickard 1985, Wilson & de Hedouville 1985). The inland belt does not contain the early slaty cleavage and is characterised by inclined, tight to isoclinal chevron folds cut by high angle reverse faults (Fig. 3; profiles A-A' and B-B') (Fergusson & Vandenberg 1990). Fossils indicate that the turbidite sequence is Early Ordovician and is occasionally associated with Late Ordovician black shale (Powell 1983, Glen *et al.* 1990, Stewart & Glen 1991).

The inland facies (Powell 1983) was considered to be distinct on the basis of slightly different sediment sources and paleocurrents, and to represent sediments deposited in a fore-arc basin, whilst the coastal facies represented the outer-arc slope and imbricated zone of an Ordovician accretionary prism (Powell 1983, 1984). Recent workers have argued that in terms of sedimentology the two facies are indistinguishable, and the forearc/accretionary prism model for sedimentation has been rejected (Vandenberg & Stewart 1992).

Chert

Underlying the turbidites is a sequence of radiolarian chert, volcanic breccia, pillow lava, black shale, pelite and limestone (Wilson 1968, Bischoff & Prendergast 1987). Late Cambrian to Late Ordovician fossils occur in this sequence at Narooma (Stewart & Glen 1991). Mid Cambrian to Late Ordovician fossils occur at Batemans Bay (Jenkins *et al.* 1982, Bischoff & Prendergast 1987). The chert commonly has the appearance of silicified sand or mudstone and the formation may represent the most distal facies of a turbidite fan. Within this formation the contact between the pillow lavas and chert is either conformable or a tectonic contact at a low angle to bedding (Wilson 1968, Miller 1994). The pillow lava and volcanic breccia is at the base of the formation at Narooma (Fig. 5) and at Batemans Bay (Fig. 3; profile D-D'). South of Batemans Bay, at Melville Point, the contact between the chert and turbidite sequence is conformable (Etheridge *et al.* 1973). The chert below this conformable contact is Late Cambrian to Early Ordovician (Bischoff & Prendergast 1987). At Malla-coota, south of Bermagui, thin beds of Late Ordovician chert have also been observed within interbedded greywacke and mudstone sequences (Wilson *et al.* 1982). In most areas the contact between the chert and turbidite sequence is defined by a high strain zone. At Narooma (Fig. 4) there is an age reversal across this high strain zone with Early Ordovician turbidite overlying Late Cambrian to Late Ordovician chert. Fossils also indicate repetition of stratigraphic section within the chert sequence (Fig. 3; profile D-D', Fig. 4), which has been inferred to represent fault imbrication at Batemans Bay (Bischoff & Prendergast 1987) and at Narooma.

Block-in-matrix melange

The structurally lowest unit (Bogolo Formation) of the imbricate stack is a block-in-matrix melange (Fig. 7a). The blocks have pod-like form and are composed of

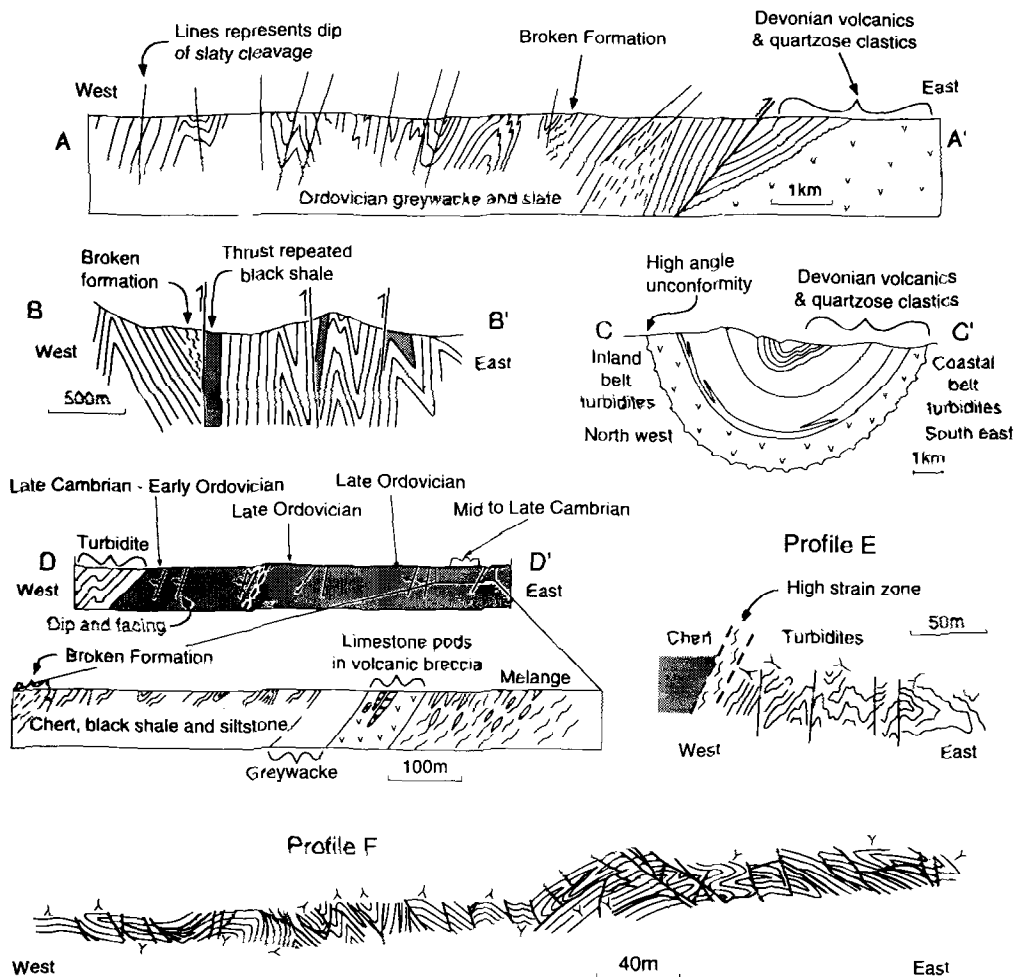


Fig. 3. Structural profiles through parts of the Narooma Accretionary Complex. A-A' and B-B' show typical structure of the 'inland' structural belt (modified from Fergusson & VandenBerg 1990). C-C' shows synclinal closure within Late Devonian 'Lambie' facies cover sequence (from Powell 1983). D-D' shows imbricated, westwards dipping chert-turbidite sequence of the 'coastal' belt (modified from Bischoff & Prendergast 1987). Profiles E and F show refolded isoclinal recumbent folds in the turbidites of the 'coastal' structural belt (E is modified from Williams 1971).

chert, greywacke and rare pillow lava. Pod size varies from clasts of sizes similar to the matrix (Fig. 7b) to massive truck sized lenses (Fig. 7c). Limited point counting suggests the greywacke pods are of a similar provenance to the greywacke of the overlying turbidite sequence (Miller 1994). Chert in the melange, however, has a different character from that found in the overlying sequence (I.A. Stewart pers. com., 1995).

The pods within the melange are poorly sorted and are randomly distributed in the matrix. They have been flattened and extended, resulting in some pods undergoing boudinage (Fig. 7d). As a result, the majority of the pods at Narooma have their long axis parallel to the strike of the anticlinorium (Fig. 9). However, some pods have their long axes at a high angle to strike, suggesting that the blocks were originally randomly oriented prior to the strong tectonic overprint. In some areas there appears to have been competency contrasts between the chert and greywacke pods. As a result some chert pods have been tectonically stretched across the entire exposure giving the chert the appearance of being interbedded with the mud matrix. Apart from some undulose

extinction in quartz, there is a distinct lack of microstructure in the necked regions of the greywacke pods (Fig. 7e). The long axes of the pods are parallel to a stretching lineation marked by symmetrical pressure shadows around framboidal pyrites (Fig. 7f), book or pull apart chlorite (Fig. 7g), and the long axes of quartz-rich lenses within the matrix (Fig. 7h). At Narooma, this lineation trends approximately 330° -parallel to the trend of the regional anticlinorium.

Reorientation, extension and flattening of the pods appear to be synchronous with the formation of the pervasive foliation in the matrix. This foliation is now folded into upright tight to isoclinal folds that are oriented in a similar fashion to the dominant fold set within the turbidite sequence. The foliation is either a fine slaty cleavage that commonly wraps around the pods or alternatively is defined by flattened and extended quartz-rich lenses (Fig. 7b). The foliation is defined by anastomosing white mica and chlorite that envelops quartz-rich lenses and rootless folds (Fig. 7h) that are disrupted by boudinage and shears at a low angle to the foliation. Some quartz-rich lenses preserve an earlier

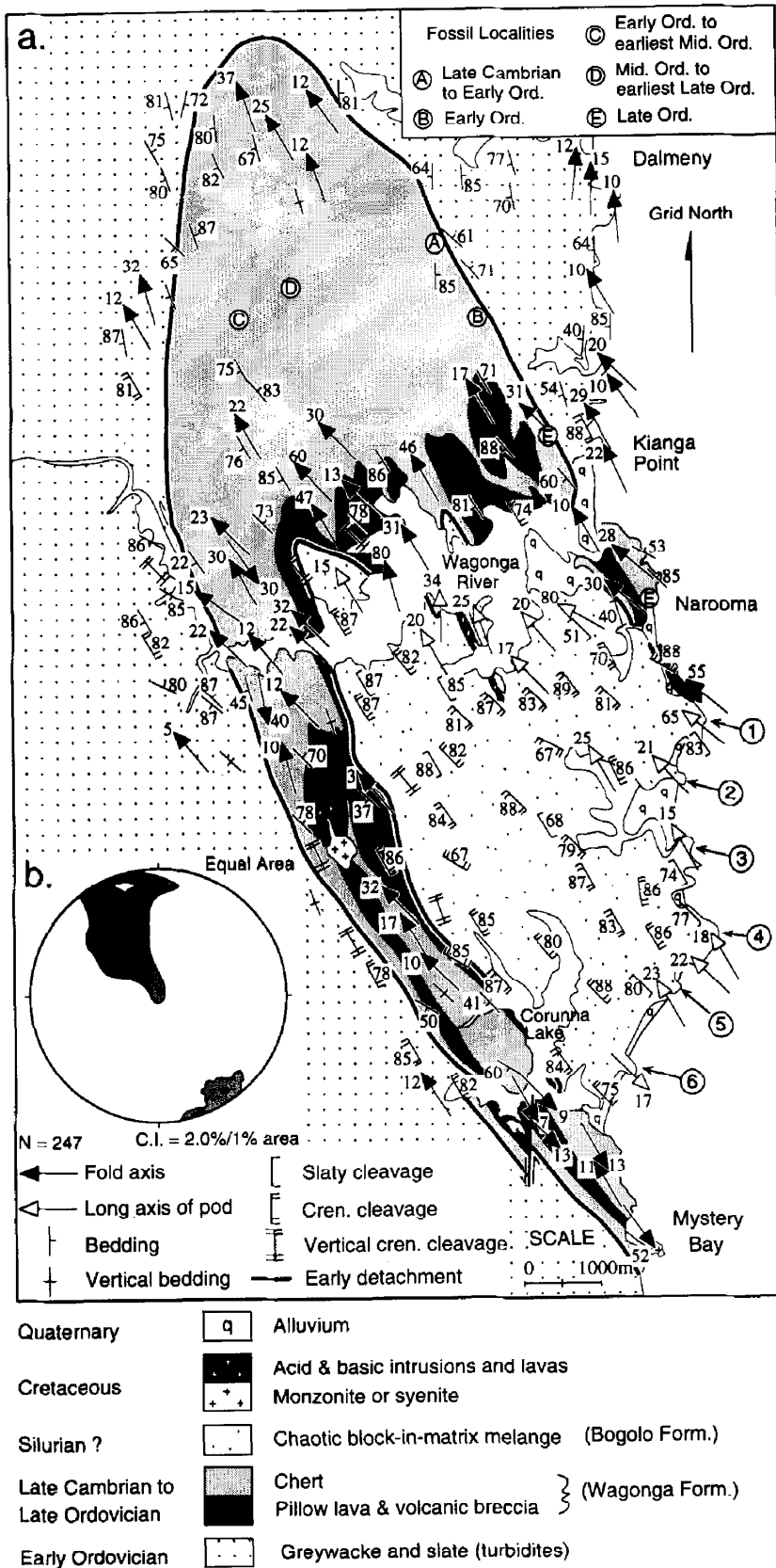


Fig. 4. (a) Structural map of the Narooma anticlinorium showing the lowest structural levels of the accretionary complex (modified from Wilson 1968). Contacts between turbidites, chert, and chaotic block-in-matrix melange are tectonic. Biostratigraphic ages are from Stewart & Glen (1991). Numbers indicate location of data plotted on stereonets in Fig. 9. (b) Stereographic projection of fold axes measured across the Narooma Anticlinorium. Dual maxima reflect Dalmeny fold set (N) and Narooma fold set (NNW).

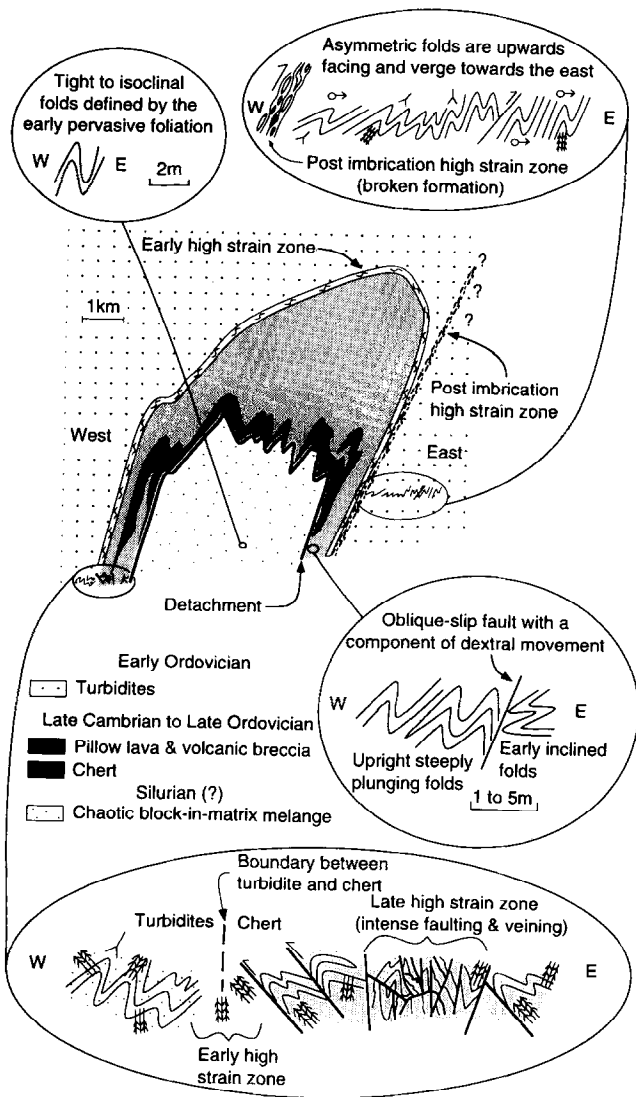


Fig. 5. Structural profile of the Narooma anticlinorium constructed by down-plunge projection of the map (Fig. 4). Insets show structural relationships within chert and/or turbidites at different levels and positions in the structure (based on Miller 1994). Positions of detachments and high strain zones within the accretionary complex are indicated.

random alignment of mica and there is no evidence for any earlier fabrics. Asymmetric shear indicators are rare and give conflicting senses of shear.

The foliation and associated extension lineation within the chaotic block-in-matrix melange are clearly early-formed as they have been affected by all folding events observed within the coherent chert-turbidite sequence. Although the pervasive foliation is associated with boudinage and disruption of the chaotic block-in-matrix melange, the blocks within the melange appear to have been in place and randomly oriented prior to the development of the foliation.

Blocks within the melange do not have faceted and slickensided faces (Moore & Allwardt 1980). This, combined with the lack of deformation microstructure in the necked regions of the elongated greywacke pods, indicates an origin either by soft sediment deformation or initial disruption at a low grade of metamorphism. Such

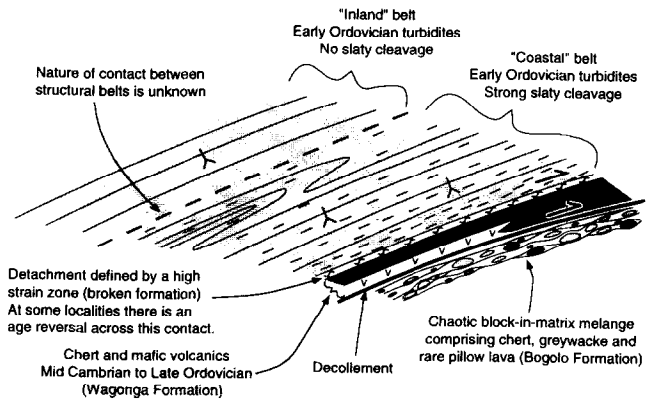


Fig. 6. Generalised imbricate stacking within the Narooma accretionary complex. The stacking order is clearly established within the Narooma anticlinorium (see Fig. 4) and at Batemans Bay (see Fig. 3: D-D'). The upper part of the 'coastal' structural belt contains isoclinal, recumbent folds and develops a pronounced bedding-parallel fabric towards the main detachment between chert and turbidites. Dashed lines represent bedding-parallel cleavage.

melanges can be generated by (1) backflow within the subducted sediment, (2) a sedimentary slump or olistostrome, and (3) diapirism (Lash 1985, Barber *et al.* 1986, Cloos & Shreve 1988, Needham & MacKenzie 1988).

Given that the greywacke pods within the melange appear to be similar to the greywacke in the overlying turbidite sequence, it is likely that the melange has been derived from sediment that was laterally equivalent (but not necessarily identical) to the overlying chert and turbidite sequences. The current structural position of the melange requires that it has been tectonically emplaced or underplated beneath the chert and turbidites. The contact between the chaotic block-in-matrix melange and the overlying chert and volcanics (Wagonga Formation) truncates bedding and appears to be tectonic (Fig. 4). The presence of mid to Late Cambrian fossils in a limestone layer directly above this melange at Batemans Bay (Bischoff & Prendergast 1987) also supports this interpretation. If the melange and limestones at Batemans Bay are part of the same conformable stratigraphic sequence, then a mid-Cambrian source (or older) is required for the melange. In this scenario the source would have to contain greywacke, chert and volcanics very similar to the mid-Cambrian to Late Ordovician sequences.

BROKEN FORMATION AND DETACHMENT FAULTS

Tectonic melange/broken formation is most pronounced along the contact between the chert and turbidite units (Fig. 3; profile E, Fig. 5). The broken formation has developed by early bedding-parallel disruption (Fig. 8a) of both the turbidite sequence and the chert. The layering within the broken formation is folded or crenulated by all later deformations observed within coherent bedding. This layering is frequently lenticular exhibiting pinch and swell structure, with



Fig. 7. Block-in-matrix melange. (a) Pods of turbidite within the chaotic block-in-matrix melange. Note book is 12 x 18 cm. (b) Flattened and extended clasts defining the pervasive foliation within the melange. Coin is 1.8 cm in diameter. (c) Massive blocks of chert within the melange. Blocks are approximately 12 m high. (d) Partially boudinaged chert block. Lens cap is 5 cm in diameter. (e) Photomicrograph from the necked region of a turbidite block. Note lack of deformation microstructure indicating pod formed pretiltification. Crossed polars, base of photomicrograph 4.3 mm. (f) Pressure shadows around framboidal pyrite defined by chlorite and quartz. Plane polarised light, base of photomicrograph 1.1 mm. (g) 'Pull apart' chlorite. Plane polarised light, base of photomicrograph 0.17 mm. (h) Pervasive foliation within mud matrix, defined by elongate quartz-rich lenses, rootless folds, white mica and chlorite. Crossed polars, base of photomicrograph 2.1 mm.

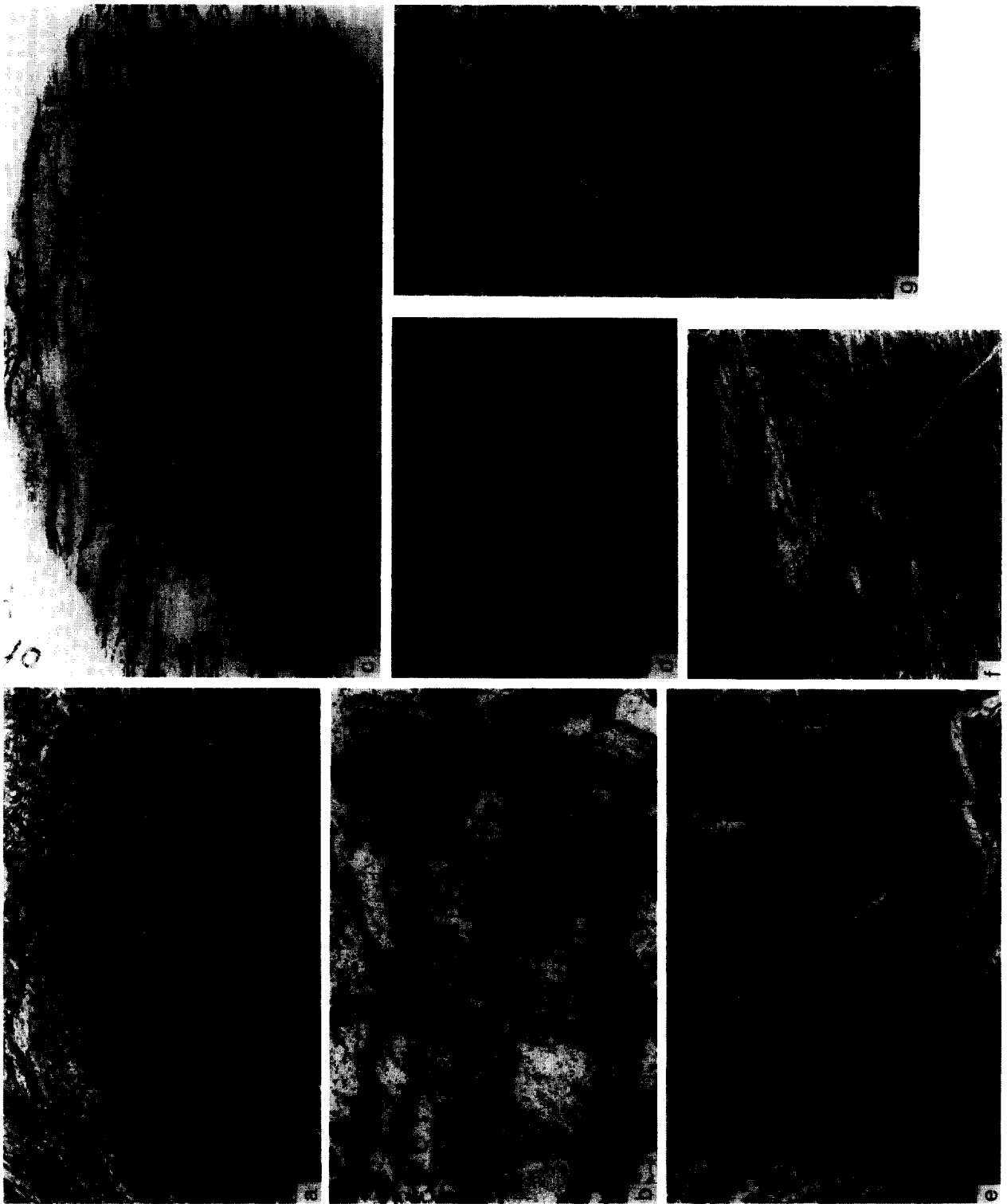


Fig. 8.

marked stylolitic contacts and extensive dilational veining indicative of pressure solution (Fig. 8b). The appearance is commonly that of a low grade mylonite (Fig. 8c), although there is no evidence for grain size reduction nor alignment of c-axes. In such zones bedding is completely broken into elongate, pod-like, carbonaceous siliceous lenses in a matrix of white mica and chlorite. Individual lenses are in places partially disrupted by extensional shear bands and via symmetric and asymmetric boudinage. Discrete bands of shear that are slightly oblique to the main foliation (Fig. 8c) and S-C fabrics (Fig. 8d) both indicate an initial southwest over northeast movement sense. The mylonitic fabric in the high strain zone is transitional into coherent bedding with a strong sub-parallel slaty cleavage (Figs. 8e–g). In some regions this very pronounced slaty cleavage cross-cuts bedding and is thus a tectonic and not sedimentary fabric (Powell & Rickard 1985, Wilson & de Hedouville 1985). Metamorphic white mica and chlorite, together with detrital mica, define the cleavage. It is further enhanced in pelitic layers by alternating quartzose and micaceous domains and in psammitic layers by a grain alignment accentuated by mica beards (Powell & Rickard 1985, Wilson & de Hedouville 1985). Dissolution of quartz has occurred during the formation of this early cleavage.

The chert-turbidite contact is interpreted as a detachment fault that was active during early imbrication and underplating. The non-stratigraphic nature of this contact is shown by the age inversion across the chert-turbidite contact at Narooma. Both this contact and the contact between the chert/mafic volcanic unit and block-in-matrix melange have initiated at a low angle to bedding and have therefore been previously interpreted as stratigraphic.

Broken formation has also been documented within the inland belt (Fergusson & VandenBerg 1990). This broken formation is distinct from that on the coast in that it is associated with a scaly, rather than slaty cleavage. The timing of this broken formation is not clear. In some areas the broken formation is associated with late reverse faults, whilst in other areas it is associated with dextral shear zones. This may indicate more than one generation of broken formation in the inland belt.

Early recumbent folding is observed at some localities in the Narooma accretionary complex and this reflects deformation in the vicinity of the early shear zones towards the base of the turbidite sequence (Fig. 3; profiles E and F). Early imbrication at a low angle to bedding is also common within the chert and turbidite sequence.

Later deformation in the eastern Lachlan Fold Belt has

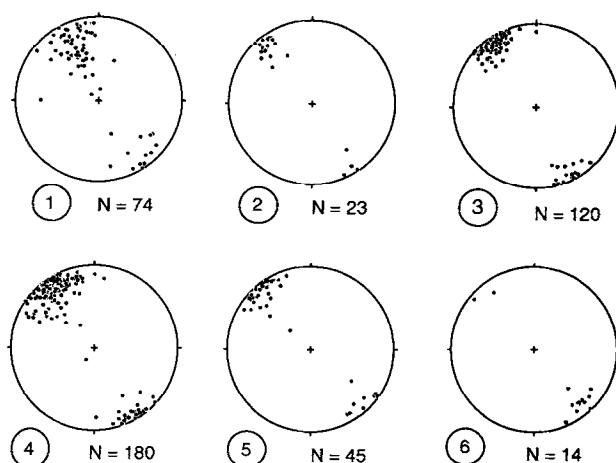


Fig. 9. Lower hemisphere projections (equal area) of long axes to pods within the block-in-matrix melange. Stereonet localities are marked on Fig. 4.

folded the imbricated stack into mesoscale, north-south trending, upright to slightly inclined folds and thrusts (Figs. 2–5). This mid-Silurian to mid-Devonian deformation (Fergusson & VandenBerg 1990) has affected both the inland and coastal structural belts. Folds in the inland structural belt develop an axial surface slaty cleavage, whilst in the coastal belt, the axial surface cleavage crenulates the earlier bedding-parallel slaty cleavage. Localised broken formation associated with thrusts is found in both the inland and coastal belts (Fig. 3; A-A', B-B', Fig. 5). This deformation is associated with a marked deformation gradient that intensifies towards the Narooma accretionary complex (Fergusson & Coney 1992b, fig. 6)

The chert sequences within the complex have deformed more readily and at a smaller wavelength relative to the turbidites (Fig. 5). The chert frequently has a second fold-set that overprints earlier folds. The later are steeply plunging and appear to be associated with oblique dextral shear. In some regions the long axes of pods within the melange are reoriented to a steeply plunging attitude by this deformation (Fig. 9; stereonet no. 1). Both sets of folds have similar microstructure and extents of veining. We interpret the observed polydeformation to represent progressive deformation and not separate distinct orogenic episodes (Wilson *et al.* 1982, Powell 1983, Glen 1992). However, some late deformation zones up to 100–200 m wide are marked by extensive veining and fold interference (Fig. 5e) and are not related to the previous progressive deformation episode. Similar zones of intense deformation have been documented south of

Fig. 8. Detachment or high strain zone between chert and turbidite. Photographs (e), (f) and (g) show a progression from the high strain zone into coherent bedding containing the bedding-parallel slaty cleavage. (a) Lenticular broken formation derived from chert within a high strain zone. Lens cap 5 cm in diameter. (b) Photomicrograph illustrating extensive dilation veining and serrated contacts between layers as a result of extensive pressure solution within initial thinly bedded chert. Crossed polars, base of photomicrograph 10 mm. (c) Disruption of thinly bedded chert via boudinage, extensional shear bands and discrete zones of dextral shear. Dip symbol strikes approximately 330°, plane polarised light, photomicrograph 79.2 mm wide. (d) S-C fabrics in high strain zone giving SW over NE sense of shear. Base of photograph 16 cm. (e) Disrupted turbidite within the high strain zone. Crossed polars, photomicrograph 10.1 mm wide. (f) Fabric within turbidite adjacent to the high strain zone. Crossed polars, photomicrograph 54.1 mm wide. (g) Bedding-parallel cleavage defined by quartz-rich lenses and white mica within coherent turbidite in the vicinity of a high strain zone. Crenulation cleavage is axial surface to an upright isoclinal fold, crossed polars base of photomicrograph 1.6 mm.

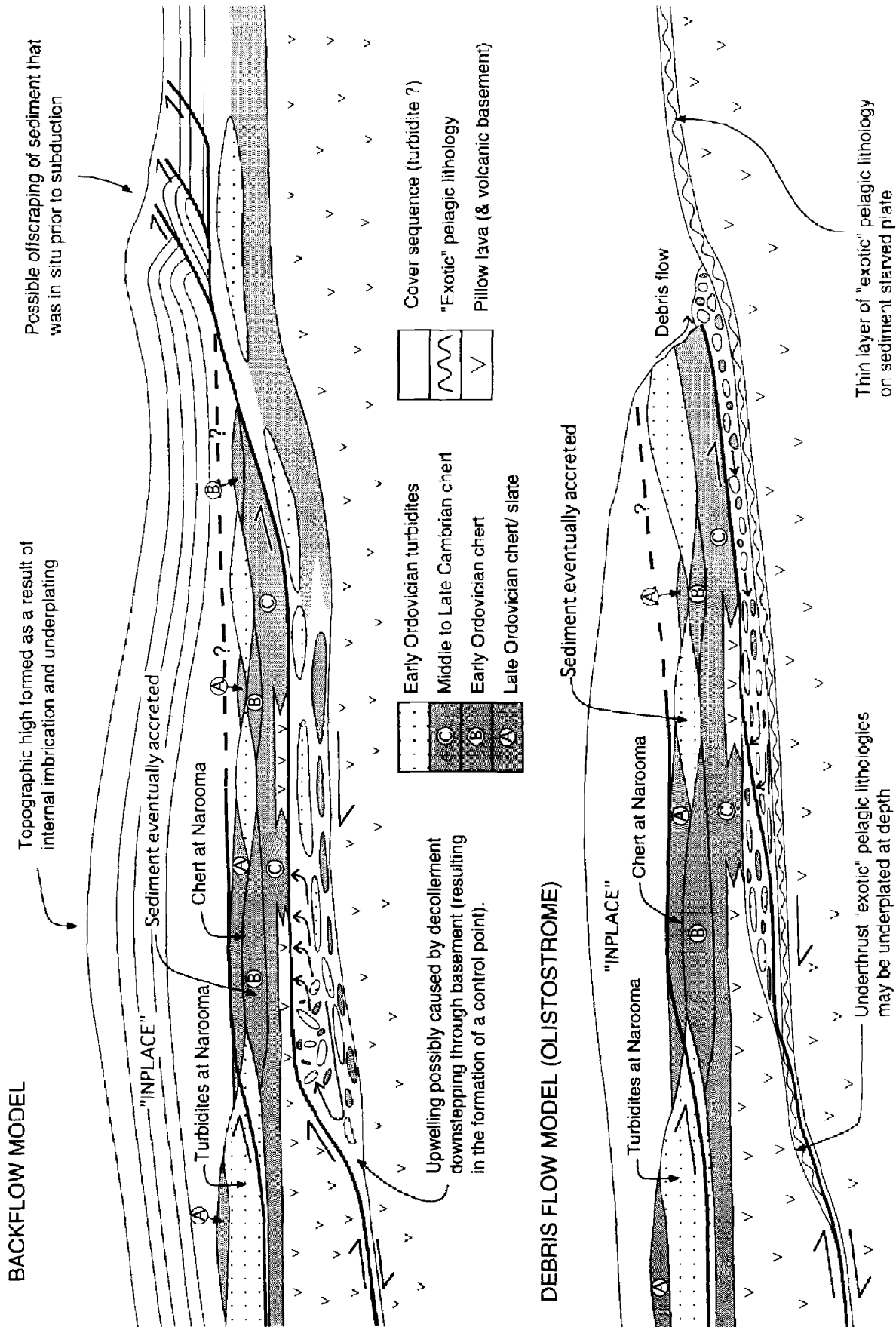


Fig. 10. Possible models for the initial deformation within the Narooma accretionary complex. Thickness of chert is overstated, all lithologies *in situ* and conformable prior to subduction (except where indicated). (a) Backflow model where downgoing 'viscous' sediment initially undergoes disruption. Constriction of sediment flow results in upwelling and formation of chaotic block-in-matrix melange during underthrusting (based on Cloos & Shreve 1988, fig. 7). (b) Debris flow (olistostrome) model where debris flows at the toe of the complex are underthrust and undergo subduction accretion.

Bermagui and their age has been tightly constrained to the mid-Devonian (Powell 1983).

STRUCTURE WITHIN THE ACCRETIONARY COMPLEX

The Narooma accretionary complex can be considered as a refolded W-dipping imbricate stack with early detachments at a low angle to bedding (Fig. 6). The sediment beneath the detachment between the turbidite sequence and chert is considered to be accreted or underplated (Fig. 10). Deformation intensity, which is partly related to lithology, increases towards the main detachment, such that structural signature within the complex varies with both lithology and structural position (Fig. 11a). In the upper part of the coastal structural belt, an early bedding-parallel fabric is folded by recumbent, asymmetric, tight to isoclinal folds (Fig. 11b). Detailed descriptions of these folds and their associated fabrics are given in Williams (1971, 1972). The bedding-parallel fabric becomes very pronounced,

particularly in sandstones, towards the high strain zones delineating the turbidite-chert contacts. This fabric (S^* , Fig. 11c & d) is clearly tectonic (Powell & Rickard 1985, Wilson & de Hedouville 1985) and must relate to a strain gradient towards the main detachment in the early stages of subduction towards the underplating. The bedding-parallel fabric is overprinted by a fanning spaced cleavage (S_{sp} , Fig. 11c), formed early during folding, and a grain alignment cleavage (S_g , Fig. 11c) which formed late in folding and is approximately axial planar to the folds (Yang & Gray 1994).

In the structurally lower part, particularly in the chert sequence, stratiform broken formation becomes common (Fig. 11e). Layers appear to have undergone a coaxial flattening deformation, resulting in a lenticular, boudinaged appearance (Fig. 8a) accentuated by stylolitic contacts and considerable extension veining (Fig. 11f). In more highly strained parts of the Narooma accretionary complex, a stretching lineation has developed parallel to fibres in pressure fringes and pull-aparts in chlorite books in the phyllitic mudstone matrix (Fig. 11i). This is matched by alignment of pod long axes in the block-in-matrix melange (Fig. 11h) and pillow long axes in basalts (Fig. 11j). Straight fibres in pressure shadows (Fig. 7f) also support a coaxial deformation sequence for the mudstone matrix to the melange. In the high strain zone at the chert-turbidite contact, S-C fabrics (Fig. 11g) indicate a southwest over northeast movement sense during non-coaxial deformation (Needham 1987, Hansen 1988).

DISCUSSION

Deformation related to offscraping at the toe of an accretionary complex is associated with faulted packets, web structure, scaly cleavage, veins and metamorphism up to zeolite facies (Sample & Moore 1987). The syntectonic chlorite-white mica assemblages in the pelitic rocks of the Narooma accretionary complex indicate that the metamorphic grade during early imbrication is too high for offscraping. B^0 values from white mica and illite crystallinity determinations indicate lower prehnite-pumpellyite conditions (R. Offler pers. comm. 1996). The higher metamorphic grade and the low angle shear zones or detachments between accreted packets in the coastal belt is typical of underplating (Byrne 1986, Sample & Fisher 1986, Fisher & Byrne 1992).

The Narooma accretionary complex has broad similarities with the deeper levels of the Kodiak Islands accretionary complex in Alaska (Moore & Allwardt 1980, Sample & Fisher 1986, Sample & Moore 1987, Fisher & Byrne 1992) and the Shimanto Complex of Japan (MacKenzie *et al.* 1987, Ditullio & Byrne 1990, Taira *et al.* 1992). In both regions underplating is associated with a slaty cleavage (Sample & Moore 1987, Fisher & Byrne 1992, fig. 5). The Alaskan complex is defined by five fault bounded units which show a decrease in age seawards (Sample & Fisher 1986, Fisher & Byrne 1987, Sample & Moore 1987). Refolded recumbent folds

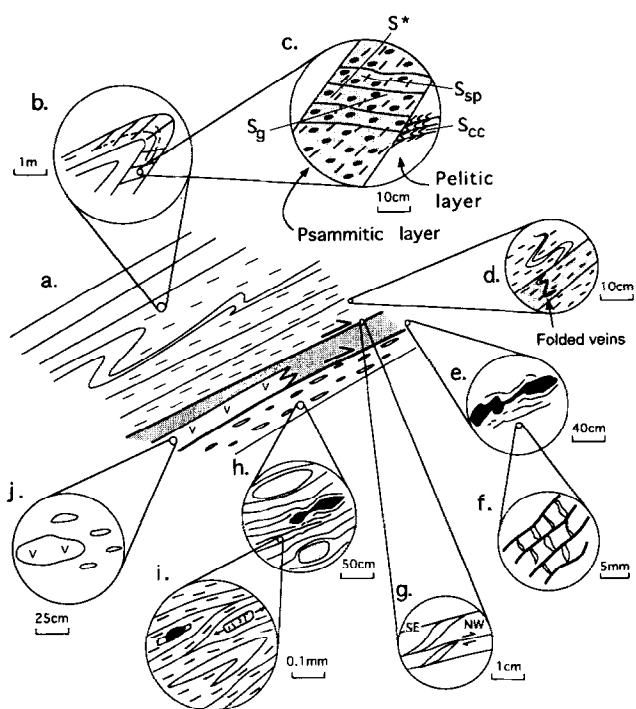


Fig. 11. Structural signature of Narooma accretionary complex. (a) Composite profile showing imbricated, west-dipping stack of turbidite, chert, pillow basalt and melange. (b) Tight anticlinal fold-closure in turbidites. (c) Multiple cleavages within greywacke layer (limb of fold in 'b'); S^* is bedding-parallel cleavage, S_{sp} is spaced cleavage in greywacke, S_g is grain alignment cleavage in greywacke, S_{cc} crenulation cleavage in pelite with bedding-parallel cleavage. (d) Bedding-parallel fabric and associated buckled quartz veins within turbidite. (e) Stratiform broken formation in chert. (f) Chert layers within broken formation showing stylolitic contacts and extensive veining. (g) S-C structure in high strain zone along chert-turbidite contact (top to the NE). (h) Elongate greywacke and chert clasts in block-in-matrix melange. (i) Phyllitic 'mudstone' matrix of block-in-matrix melange, showing rootless isoclinal fold hinges, pressure fringes on pyrite, pull-apart chlorite books and a strong white mica fabric. (j) Deformed pillows in pillow basalt.

have been observed in the Shimanto accretionary complex (Hibbard & Karig 1987, fig. 5, Needham & MacKenzie 1988, fig. 7) and in the central belt of the Kodiak accretionary complex (Sample & Fisher 1986, fig. 2).

Previous workers have argued the chert is an accreted exotic terrane (Powell 1983, Bischoff & Prendergast 1987, Glen 1993). However, the key problem with an exotic terrane model is that the chert is conformable and interbedded with the turbidites (Etheridge *et al.* 1973, Wilson *et al.* 1982). Whilst some of the chert is mid to Late Cambrian, most is Early Ordovician, which is the same age or younger than the turbidites (Stewart & Glen 1991). All the evidence suggests that, at this level of exposure, the Narooma accretionary complex comprises sediment that was autochthonous prior to subduction.

Implications for underplating

Subduction zones show changing character, deformation mechanisms and structural style with depth (Sample & Moore 1987, fig. 3, MacKenzie *et al.* 1987, fig. 4, Kimura & Mukai 1991, fig. 19). Upper levels are characterised by offscraping and frontal accretion, whereas lower levels reflect the processes of underplating. Underplating has previously been considered to occur by duplex accretion involving footwall collapse and propagation of the basal detachment into the subducted sediment of the downgoing slab (Platt *et al.* 1985, Sample & Fisher 1986, Sample & Moore 1987, fig. 3, Kimura & Mukai 1991, fig. 19). Underplating accretion at deeper levels may also take place by imbricate stacking of thrust nappes. This has been documented in the Gokase River area of the Shimanto Belt accretionary complex, Japan (Needham & MacKenzie 1988).

In the Narooma accretionary complex, the Bermagui deformation style is characteristic of underplating at intermediate to shallow levels. There is no definitive evidence for duplexing, but stratigraphic age reversals indicate some form of imbrication in the lower part of the complex. The early bedding-parallel cleavage probably reflects underthrusting early in subduction (Fisher & Byrne 1992). Progressive deformation during emplacement led to the development of asymmetric, tight to isoclinal recumbent folds in turbidites (e.g. Williams 1972, plate 1).

In the lowest levels of the complex, development of intense foliation where early veins and sedimentary layering have been completely transposed, reflects a marked strain gradient into the main detachment (Fisher & Byrne 1992). High strains are reflected by a marked alignment of deformed, prolate pods of greywacke and chert within strongly foliated phyllitic mudstone matrix within block-in-matrix melange, and within broken formation in chert. Coaxial flattening has been important in the development of the Narooma accretionary complex, as recorded by stratal disruption indicators and pressure shadows on pyrite.

Subduction zone geometry and timing

The subduction zone geometry cannot be determined from the Narooma accretionary complex itself due largely to the effects of superimposed deformations. The geometry, however, can be derived from the gross geometry of the inland belt. The overall vergence of this deformation is to the east, supporting east-directed transport above an inferred west-dipping subduction zone (Fergusson & VandenBerg 1990, Fergusson & Coney 1992b). During development of the Narooma accretionary complex, deformation changed from imbrication at a low angle to bedding to intense shortening via folding and thrusting. The early extension lineation, associated with the strongly deformed lower part of the complex, is oblique to the later structural trends that have an east-directed transport direction. This may indicate that the shortening is due to a change in the convergence vector from early oblique subduction to a more front-on style of subduction. At this stage the detachments associated with the earlier phase of subduction were abandoned. This later deformation has affected both the inland and coastal structural belts. The presence of steeply plunging folds associated with oblique-slip faults within the chert sequence suggests that there may also have been an oblique dextral component to the subduction during the later deformation.

The timing of the early oblique subduction is constrained by the youngest rock type caught up in the complex (Late Ordovician) and by the onset of massive shortening in the mid Silurian to mid-Devonian (Fergusson & VandenBerg 1990). We favour an Early to mid-Silurian age for the early oblique subduction. Early Silurian structures in the central Lachlan Fold Belt (Benambran Orogeny) are also oblique to the later structural styles and have been related to dextral transpression as a result of oblique convergence (Powell 1984).

CONCLUSIONS

The Narooma accretionary complex in the Lachlan Fold belt of southeastern Australia represents an intermediate to shallow level example of underplating. Underplating in subduction complexes has previously been considered to occur by duplex accretion. The deformation style incorporates an early bedding-parallel fabric, isoclinal-recumbent folding, poly-deformation and differentiated layering in greywackes. There is no evidence for duplexing, and major lithologic boundaries in the coastal structural belt are generally high strain zones subparallel to the gross layering.

The structural complexity including broken formation, chaotic block-in-matrix melange and large scale imbrication is atypical of deformation within the Lachlan Fold Belt, but is indicative of a subduction zone. The gross structural zonation within the Narooma accretionary complex shown by the inland and coastal structural belts

shows similarities to the Kodiak and Shimanto accretionary complexes.

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