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Diapirism and structural thickening in an Early Palaeozoic subduction complex, southeastern New South Wales, Australia

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Abstract

A major problem in the study of subduction complexes has been to distinguish between processes of mud diapirism, deformation of unlithified sediments, frontal accretion and underplating. In the Batemans Bay area, Cambro–Ordovician rocks of the south coast of New South Wales (eastern Australia) contain common mud-rich mélanges that occur amongst an imbricated succession of Early to Middle Ordovician quartz turbidites, Late Ordovician black mudstone and chert, Cambrian limestone and mafic volcanics. An early set of fluidal obliquely trending folds are restricted to the Late Ordovician black mudstone and chert and probably formed by gravitational down-slope movement on a lower trench slope. Features indicative of deformation of unlithified sediments are still preserved and include mud injections, delicate small-scale faulting and the absence of grain-scale deformation. Tight to isoclinal north–south folds with axial planar west-dipping cleavage overprint all units and formed during the younger main-phase deformation that post-dated early deformation in the prism. The mélange has been strongly overprinted by this main-phase deformation. Early mélange formation is attributed to mud diapirism involving intrusion along early accretionary faults, bedding planes and in pipe-like features resulting in chaotic outcrop and map patterns. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Diapirism; Structural thickening; Subduction complex

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1. Introduction

Modern subduction zones are characterised by various structural processes including frontal accretion, underplating and tectonic erosion (von Huene and Scholl, 1991). Frontal accretion involves intricate imbrication where oceanic units and trench-filling turbidites are repeated hundreds if not thousands of times (Kimura and Ludden, 1995). Underplating of oceanic sediments and igneous basement to depth below subduction complexes result in structural thickening of the complex and accompanying uplift. Subduction zone deformation has commonly affected unconsolidated successions resulting in soft-sediment disruption and mobilisation of low-density masses of mainly mud and their subsequent injection into overlying units (Pickering et al., 1988). The ultimate result is widespread mud diapirism, the formation of mud volcanoes and associated debris flows that have been documented on the lower slopes of some subduction complexes (Barber and Brown, 1988; Robertson et al., 1996).

In ancient subduction complexes attempts to identify processes are complicated as only the final product of the accretionary history can be analysed. Attempts to overcome this problem have relied upon using the standard techniques of structural analysis with establishment of overprinting criteria, shear-sense indicators and mapping them throughout the wedge (Onishi and Kimura, 1995; Kusky and Bradley, 1999). This approach has established that growth of subduction complexes initiates with the development of accretionary thrusting and formation of structures commonly in unconsolidated sediment. Folding and cleavage development occurs after thickening of the wedge to the point where depth of burial allows these processes to become the dominant mode of deformation.

Cambro–Ordovician rocks exposed along the New South Wales south coast are part of the Lachlan Fold Belt of southeastern Australia and are regarded as a subduction complex associated with an Ordovician island arc in central New South Wales (Figs. 1 and 2; Jenkins et al., 1982; Powell, 1983, 1984; Miller and Gray, 1996). Continuous coastal exposure occurs in numerous rocky headlands and several

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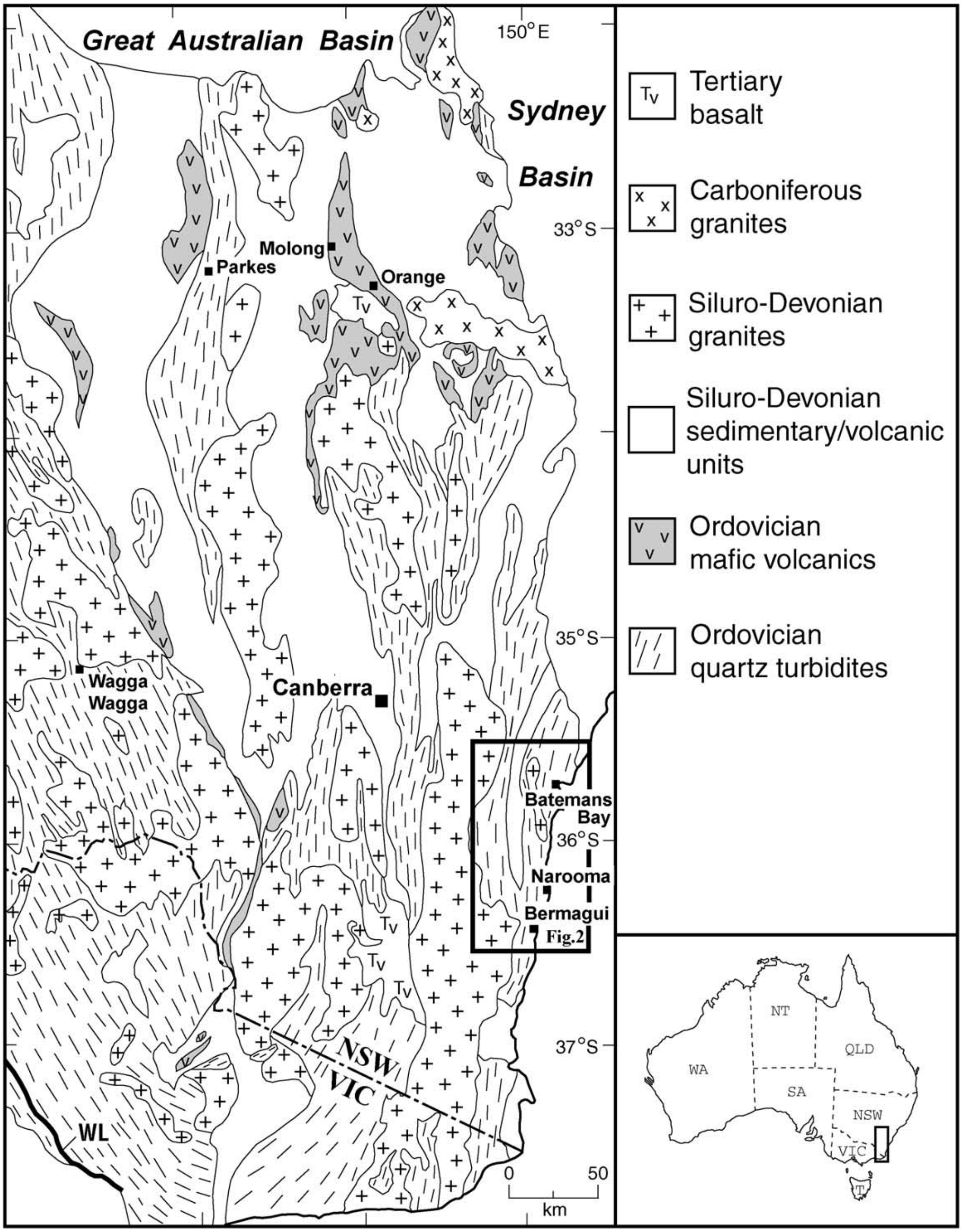

Fig. 1. Map of the eastern Lachlan Fold Belt, southeastern Australia with main outcrop of the Ordovician quartz turbidite succession and the Ordovician mafic volcanic succession (island arc). WL = Wonnangatta Line. Insets shows location in Australia.

units are developed including widespread chaotic block-in-matrix mélange (Bischoff and Prendergast, 1987). In the Narooma area (Fig. 2), Miller and Gray (1996, 1997) undertook detailed mapping with analysis of microstructures and attributed the initial formation of a block-in-matrix mélange to either a debris flow model or a back-flow model involving disruption during underthrusting. Offler et al. (1998) determined middle to upper anchizone metamorphism from crystallinity and b_0 spacing of micas and inferred a low geothermal gradient. We have undertaken detailed mapping of the mélange and associated units south of Batemans Bay (Fig. 2), 40 km north of Narooma, and have found that mélange has complicated field relationships consistent with mud diapirism rather than either an olistostrome or

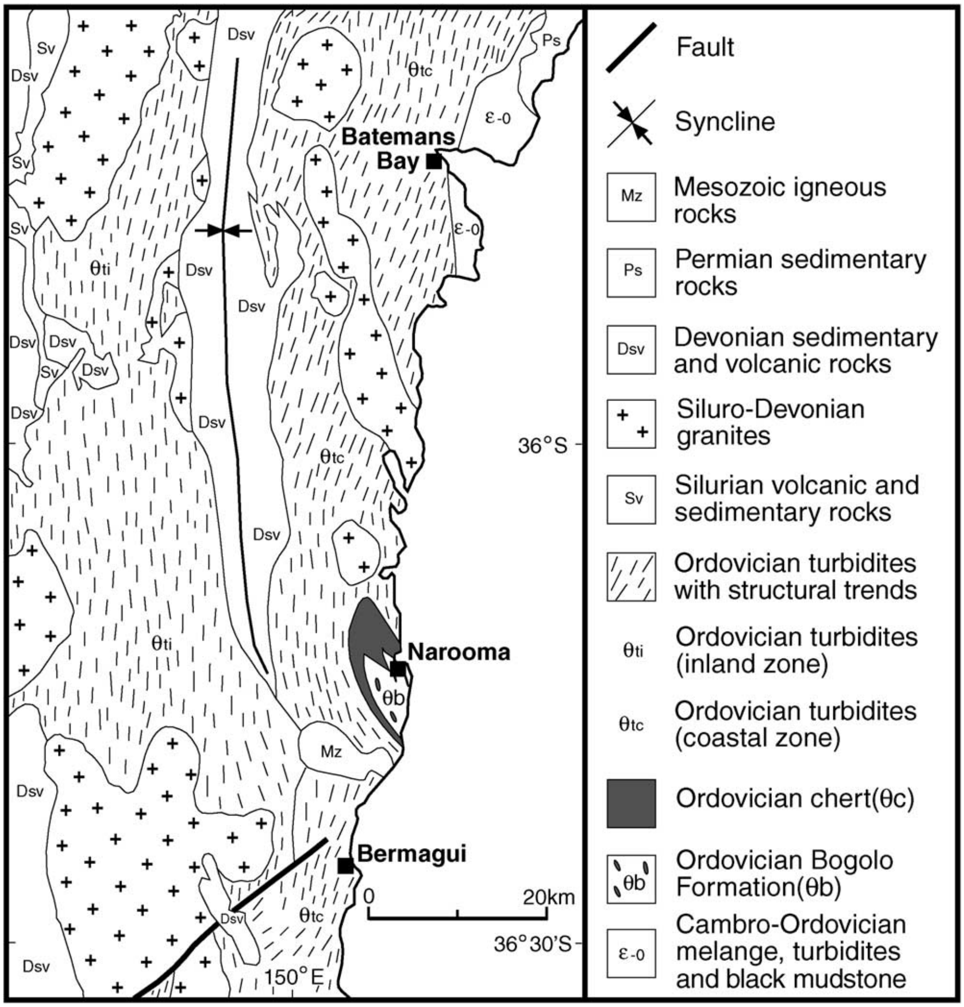

Fig. 2. Subduction complex along the south coast of New South Wales with trends of bedding/cleavage and major units. See Fig. 1 for location.

tectonic origin for the initial block-in-matrix fabrics. These exposures serve to illustrate the difficulties of establishing the deformation history of ancient subduction complexes and recognising the roles of underplating and frontal accretion and distinguishing these from later deformation.

2. Regional geologic framework

The Lachlan Fold Belt is part of the Gondwana continental margin that faced the Pacific Ocean in the Cambrian to Carboniferous and formed the inner part of the Tasmanides of eastern Australia (Coney et al., 1990; Foster et al., 1999). The belt has a width of 700 km in Victoria and extends northwards into central New South Wales for over 600 km. One of the impressive features of the Lachlan Fold Belt is that intensely deformed Early Palaeozoic turbidites are found across most of the belt implying an original width possibly as much as 2000 km and indicating that a giant submarine turbidite fan must have existed (Fergusson and Coney, 1992). In the northeastern part of the belt is a wide zone of Early to mainly Late Ordovician island arc rocks with mafic to intermediate lavas, intrusions and abundant volcaniclastic rocks (Powell, 1984; Glen et al., 1998). This zone narrows to the south and eventually disappears in northeastern Victoria (Fig. 1). East of the island arc Powell (1984) inferred a forearc basin and subduction complex with the latter restricted to Cambrian and Ordovician rocks along the coast of New South Wales and up to 15 km inland (Fig. 2). The Ordovician rocks of the forearc basin consist of an Early to Middle Ordovician quartz turbidite succession derived from the Delamerian Fold Belt to the west and overlain by a Late Ordovician black shale unit (VandenBerg and Stewart, 1992; Fergusson and Tye, 1999). In Victoria these rocks are mapped around the southern termination of the island arc and farther west are underlain by a basement of Cambrian ‘infant island arc’ mafic volcanics (Crawford, 1998; Fergusson, 1998). Ordovician rocks of the Lachlan Fold Belt are overlain by widespread Siluro–Devonian volcanic and sedimentary successions and are intruded by abundant Silurian to Carboniferous granites (Coney et al., 1990).

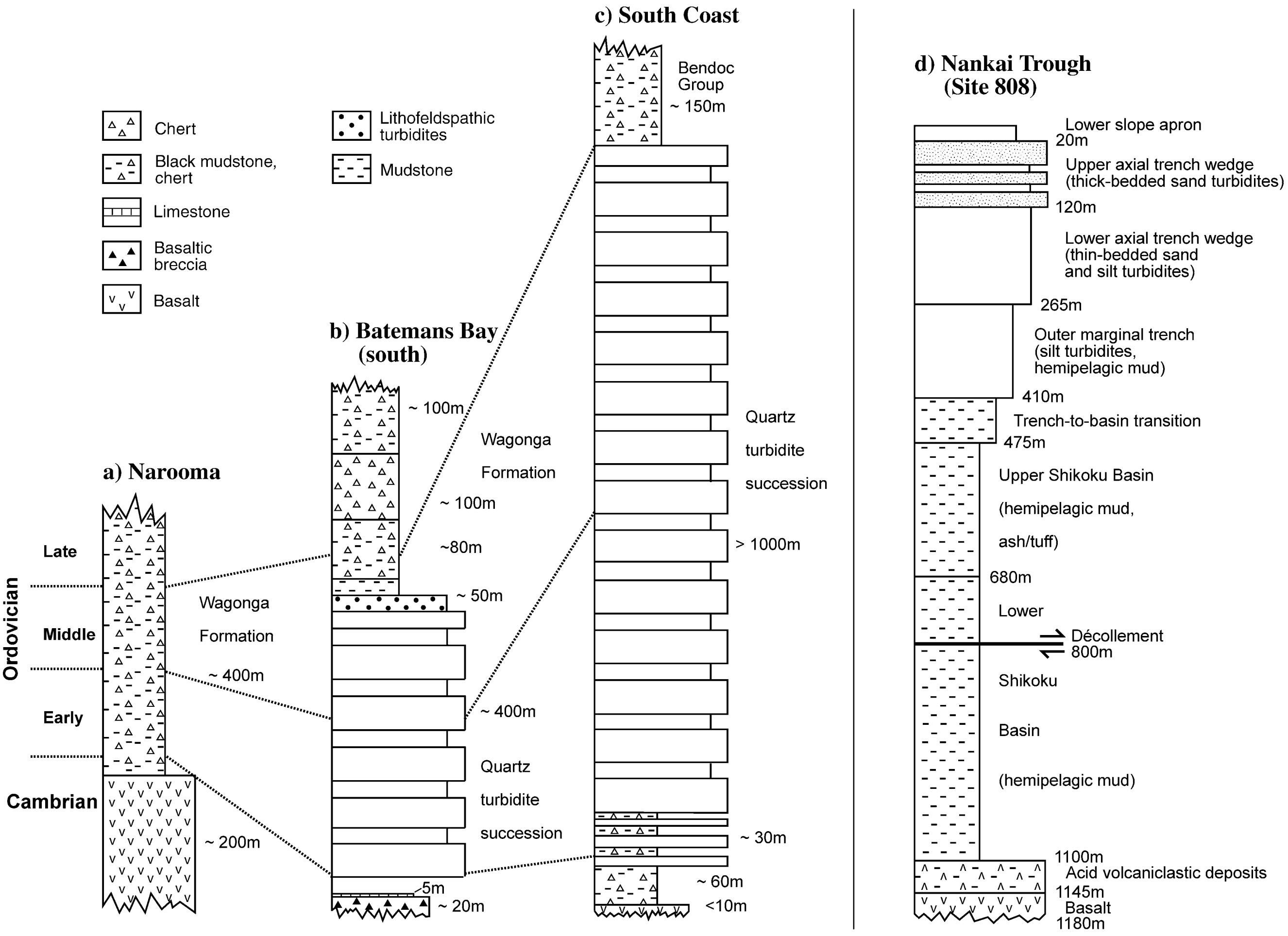

Fig. 3. Stratigraphic successions of subduction complex rocks at Narooma (a) and Batemans Bay (b) and compared with the stratigraphic succession for the dominant Ordovician succession of the south coast of New South Wales (c) and the Miocene and younger coarsening and thickening upward succession from ODP Site Hole 808, Nankai Trough (Leg 131, Shipboard Scientific Party 1991). Column (a) compiled from mapping of Wilson (1968) and Miller and Gray (1996, 1997). In (a) the Wagonga Formation is latest Cambrian/earliest Ordovician to earliest Late Ordovician age (Stewart and Glen, 1991). In (b) the thin limestone unit at the base of the section is Middle to Late Cambrian and the Wagonga Formation in the upper part of the section is late Middle Ordovician to Late Ordovician (Jenkins et al., 1982; Bischoff and Prendergast, 1987; Stewart and Glen, 1991). In (c) the basal black mudstone/chert and interbedded turbidites are latest Cambrian/earliest Ordovician and are overlain by Early to ?Middle Ordovician turbidites with the Bendoc Group of Late Ordovician age (Powell, 1983; Bischoff and Prendergast, 1987; Stewart and Glen, 1991). Stratigraphic thicknesses are estimates based on cross-sections; the 1000-m-thickness of the quartz turbidite succession in (c) is almost certainly too thin.

Deformation is intense along the New South Wales south coast with four regional deformations having been recognised with up to three sets of overprinting structures locally identified (Powell, 1983). The first deformation involved the formation of northerly trending upright, tight to isoclinal, upright to locally recumbent folds with an early slaty cleavage (S^* of Powell and Rickard, 1985) in Ordovician turbidites of the Adaminaby Group. Offler et al. (1998) presented two ^{40}Ar/^{39}Ar-plateau ages of 445 ± 2 Ma and 450 ± 3 Ma that they interpreted to indicate the timing of early metamorphism and cleavage development (S^*) in the Ordovician turbidites. ^{40}Ar/^{39}Ar and K–Ar whole rock ages in the Batemans Bay area have indicated that the regional cleavage here is of 440–400 Ma (Fergusson and Phillips, 2001). The timing of the regional cleavage-producing deformation at Batemans Bay is therefore poorly constrained, which largely reflects difficulties such as inherited material and recoil loss encountered during ^{40}Ar/^{39}Ar age analysis (Fergusson and Phillips, 2001). These problems also raise doubts about the significance of the ages of Offler et al. (1998), although these effects are considered minimal for the Bermagui sample (445 ± 2 Ma) as this area has a locally higher metamorphic grade (uppermost anchizonal to epizonal), as indicated by higher illite crystallinity (IC) values (Offler et al., 1998, fig. 11). Subsequent deformations, although of regional extent, were more local in their development and the last event was related to regional scale kinking (Powell, 1983).

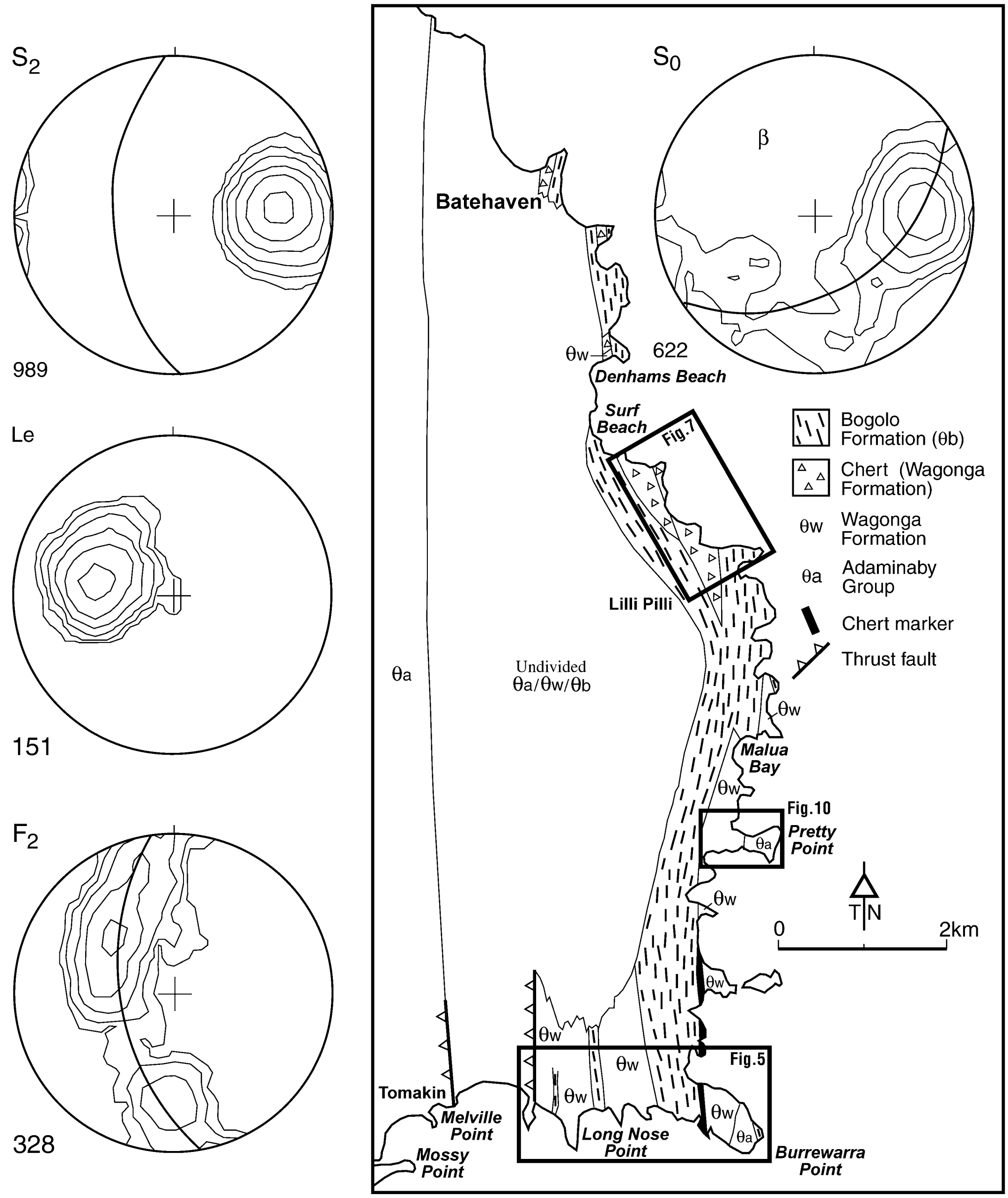

Fig. 4. Map of the coastal exposures south of Batemans Bay with locations of Figs. 5, 7 and 10. Synoptic lower hemisphere equal area stereographic projections with total bedding (S_0), total S_2, total L_e (elongation lineation in S_2) and total F_2. Poles to bedding are contoured at 1, 2, 4, 8 and 16% per 1% area with a calculated β-axis at 40°/327°. Poles to S_2 are contoured at 1, 2, 4, 8, 16 and 32% per 1% area with a preferred orientation of 58°/267°. F_2 axes are contoured at 1, 2, 4, 8 and 16% per 1% area and fall on a great circle of 62°/262°. L_e lineations are contoured at 1, 2, 4, 8, 16 and 32% per 1% area with a preferred direction of 50°/284°.

3. Stratigraphy of the subduction complex south of Batemans Bay

Along the coastline to the south of Batemans Bay the rocks have been divided into a western zone with Ordovician quartz turbidites of the Adaminaby Group (Glen, 1994) and an eastern zone with several units that include chaotic block-in-matrix mélange (Bogolo Formation), the quartz turbidite succession (Adaminaby Group), interbedded black mudstone, chert and fine sandstone (Wagonga Formation) and some Middle to Late Cambrian limestone and associated basaltic breccia (Figs. 3–5; Jenkins et al., 1982; Bischoff and Prendergast, 1987).

The Cambrian limestone and associated basaltic breccia has been regarded as a seamount that was accreted from the subducting plate (Bischoff and Prendergast, 1987). Cambrian limestone has only been found at Burrewarra Point (Fig. 5) although basaltic breccia is more widespread. Immediately to the west of the study area at Melville Point (Fig. 4), the Ordovician quartz turbidites contain thin chert beds with latest Cambrian–earliest Ordovician conodonts and conformably overlie a unit of bedded chert, black

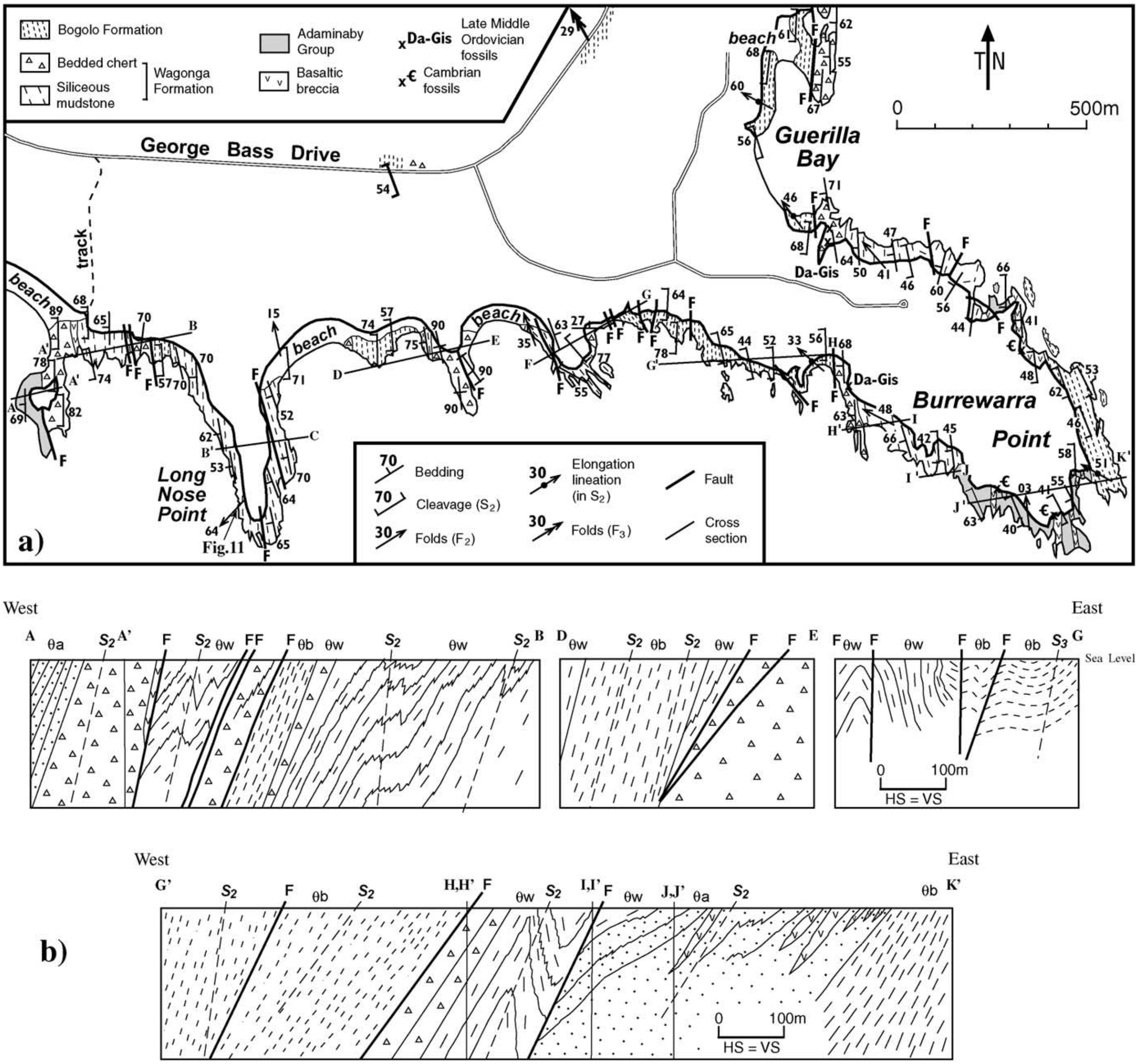

Fig. 5. Summary map (a) and cross-section (b) for the Burrewarra Point area at the southern end of the study area. Locations of cross-section lines shown in (a). Note that folds abound in the Adaminaby Group (θa) and the Wagonga Formation (θw) and at the scale of the cross-sections cannot be shown in detail. No bedding is preserved beyond a metre or so in the Bogolo Formation (θb). Note the largescale repetition of the units across the cross-section, although in particular the extent of the Wagonga Formation has been significantly enhanced by the complexity of the small-scale F_2 folding. S_2 cleavage is shown as dashed lines on the cross-section.

mudstone and underlying basalt containing latest Cambrian–earliest Ordovician conodonts near the top of the unit (Bischoff and Prendergast, 1987). Mafic volcanics are everywhere intensely altered with pervasive chloritic–carbonate and clayey alteration.

The Ordovician Adaminaby Group consists of alternating quartzose to quartz-rich sandstone and mudstone in a turbidite succession with rare intervals of bedded chert usually less than 1 m thick. Pods, lenses and thin layers (<1 m thick) of highly vesicular basalt and basaltic breccia occur within the quartz turbidites (Figs. 5 and 6a). They have not been found in the Adaminaby Group outside the study area south of Batemans Bay. The age of the Ordovician quartz turbidites along the south coast is constrained at some localities where conodonts occur in interbedded cherts, which indicate an Early to Middle Ordovician age (VandenBerg and Stewart, 1992).

The Wagonga Formation is a unit of bedded chert and black siliceous mudstone alternating with thin white siltstone and fine sandstone layers. In some areas

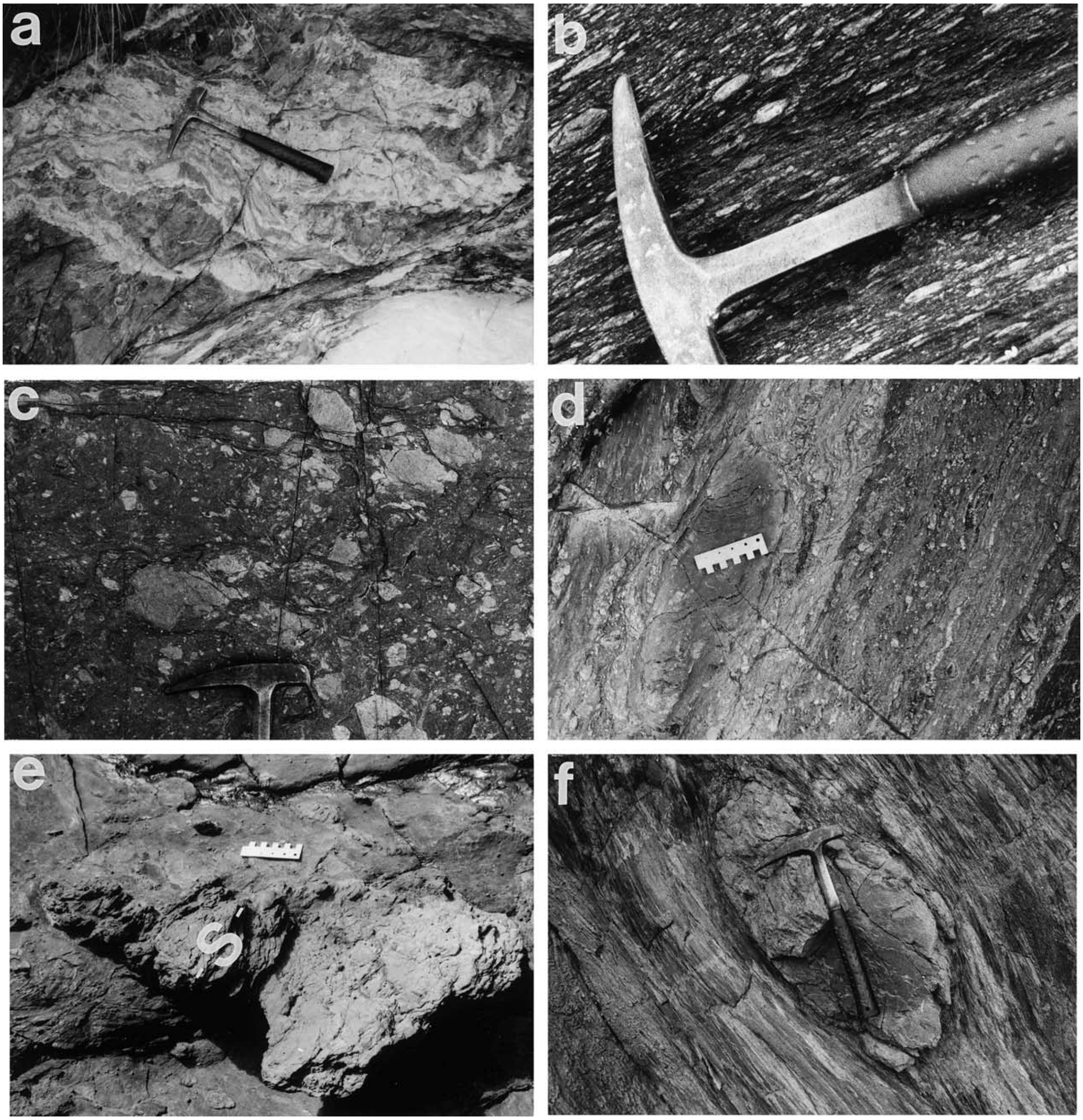

Fig. 6. (a) Light-coloured layer of altered mafic volcanics in dark-coloured mudstone of the Adaminaby Group, southern side of Burrewarra Point. Hammer 32.5 cm long for scale. (b) Highly cleaved (S_2) mélange of the Bogolo Formation with fragments of quartz sandstone, northern headland of Malua Bay. (c) Disrupted sandstone of the Adaminaby Group, southern side of Burrewarra Point. Note the lack of any stretching direction. Hammer head 16.5 cm long for scale. (d) Early layering developed in mélange of the Bogolo Formation at Malua Bay. Note fragments contained in the layering. Bar scale is 10 cm long. (e) S_2 (labelled S) cross-cutting lenticular quartz sandstone fragment in mélange of the Bogolo Formation, headland north of Lilli Pilli. (f) Asymmetric boudinage in mélange of the Bogolo Formation, Lilli Pilli. This indicates a west-over-east sense of asymmetry.

volcanic-derived sandstone is interbedded with the black mudstone. These sandstones consist wholly of mafic volcanic rock fragments and minor feldspar (albite) in contrast to the quartz-rich sandstone of the Adaminaby Group (Fergusson and Tye, 1999). Bedded chert in the Wagonga Formation is commonly black to dark grey and consists of chert layers alternating with siliceous mudstone layers with thicknesses ranging from millimetres up to 10 cm. Contacts between chert and the black siliceous mudstone are typically sharp and commonly faulted. At Narooma, conodonts found in the Wagonga Formation indicate that the unit was deposited at least intermittently throughout the whole Ordovician (Fig. 3; Stewart and Glen, 1991). South of Batemans Bay, Eastonian and Bolindian graptolites have been found in black mudstone at two localities (Jenkins et al., 1982) and latest Darriwilian–earliest Gisbornian conodonts have been found in bedded chert (Stewart and Glen, 1991; Frikken, 1997) indicating a

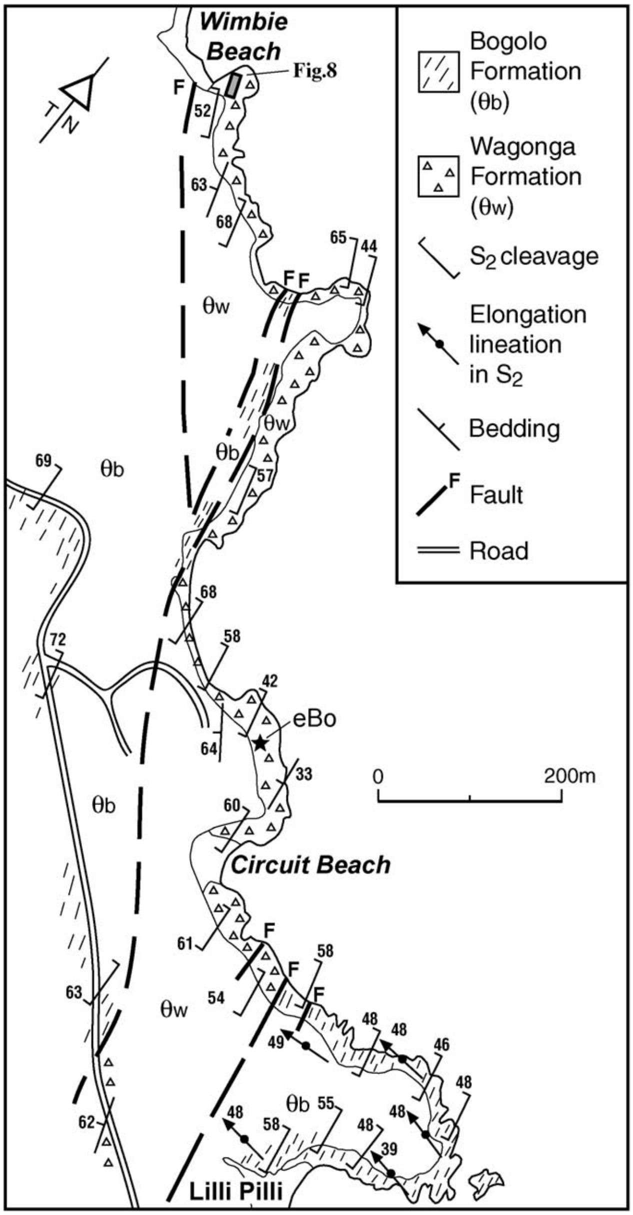

Fig. 7. Detailed map of the coastline between Wimbie Beach and Lilli Pilli. See Fig. 5 for location. Note how the Bogolo Formation forms a narrow fault-bound belt between two intensely folded belts of Wagonga Formation. Early Bolindian graptolite locality (eBo) is shown.

latest Middle to Late Ordovician age. The Wagonga Formation south of Batemans Bay therefore correlates with the Late Ordovician black shale unit (Warbisco Shale) that occurs stratigraphically above the Adaminaby Group in eastern New South Wales and Victoria (Fig. 3; VandenBerg and Stewart, 1992).

In the Narooma region, Wilson (1968) mapped a regional anticlinorium cored by the Bogolo Formation that is now recognised as a chaotic block-in-matrix mélange (Miller and Gray, 1996, 1997). In contrast, in the study area the Bogolo Formation is mapped as several strips between other rock units (Figs. 4, 5 and 7) with no apparent simple stacking order recognisable as inferred for the Narooma anticlinorium. The Bogolo Formation of the study area is a mudstone-matrix mélange with abundant fragments of quartz sandstone and less common fragments of highly vesicular basalt, siliceous mudstone and chert (Fig. 6). The proportion of mudstone is high in the mélange (>90–99%) with fragments up to several metres in length. The widespread highly vesicular basalt fragments commonly have intensely altered clayey rinds that are strung out in the matrix in comparison with their less altered cores. Locally, mélange with abundant pebble sandstone fragments has been referred to as ‘diamictite’ by Jenkins et al. (1982).

Stratigraphic development of the accreted succession is atypical when compared with the common upward coarsening and thickening successions documented in subduction complexes (Shipboard Scientific Party, 1991). The succession is overall upward fining with thickly bedded and coarse-grained sandstones near the base fining upwards in the late Middle Ordovician to black mudstone and chert of the Wagonga Formation (Fig. 3). This contrasts with the base of the Adaminaby Group at Melville Point (Fig. 3c) where a coarsening-upwards cycle is recognised at the base of the succession (Powell, 1983).

4. Early structures in the subduction complex

The most well developed structures in the coastal outcrops are tight to isoclinal folds and axial planar cleavage that are associated with the regional deformation (see Section 5). This deformation is intense and earlier structures are difficult to identify but include early folds, deformation features associated with disruption of unconsolidated sediment, early mélange fabrics, early diapirs and early faults associated with imbrication.

4.1. Early folds

In the study area, the Wagonga Formation contains mesoscopic to map-scale east–west to east–southeast-trending folds (e.g. Surf Beach; Powell, 1983, fig. 65). Axial planes are generally steeply dipping but locally dip as little as 45°, commonly to the north. They are asymmetric structures with close to open interlimb angles and are strongly refolded by the main-phase deformation (see below) resulting in dome-and-basin interference fold patterns (Fig. 8). In many rock platforms the presence of early folds is inferred from the smoothly changing gentle to steep plunges of the more abundant second-phase folds. The early folds have not been identified farther south in the Narooma anticlinorium (Miller and Gray, 1996, 1997).

The most distinctive feature of these folds, apart from their trend oblique to the regional structural grain, is the absence of any axial planar cleavage, even in the cores. Powell (1983, fig. 65) reported a local spaced axial planar cleavage in one fold hinge at Surf Beach (Fig. 4). In careful detailed mapping of outcrops here and elsewhere along the

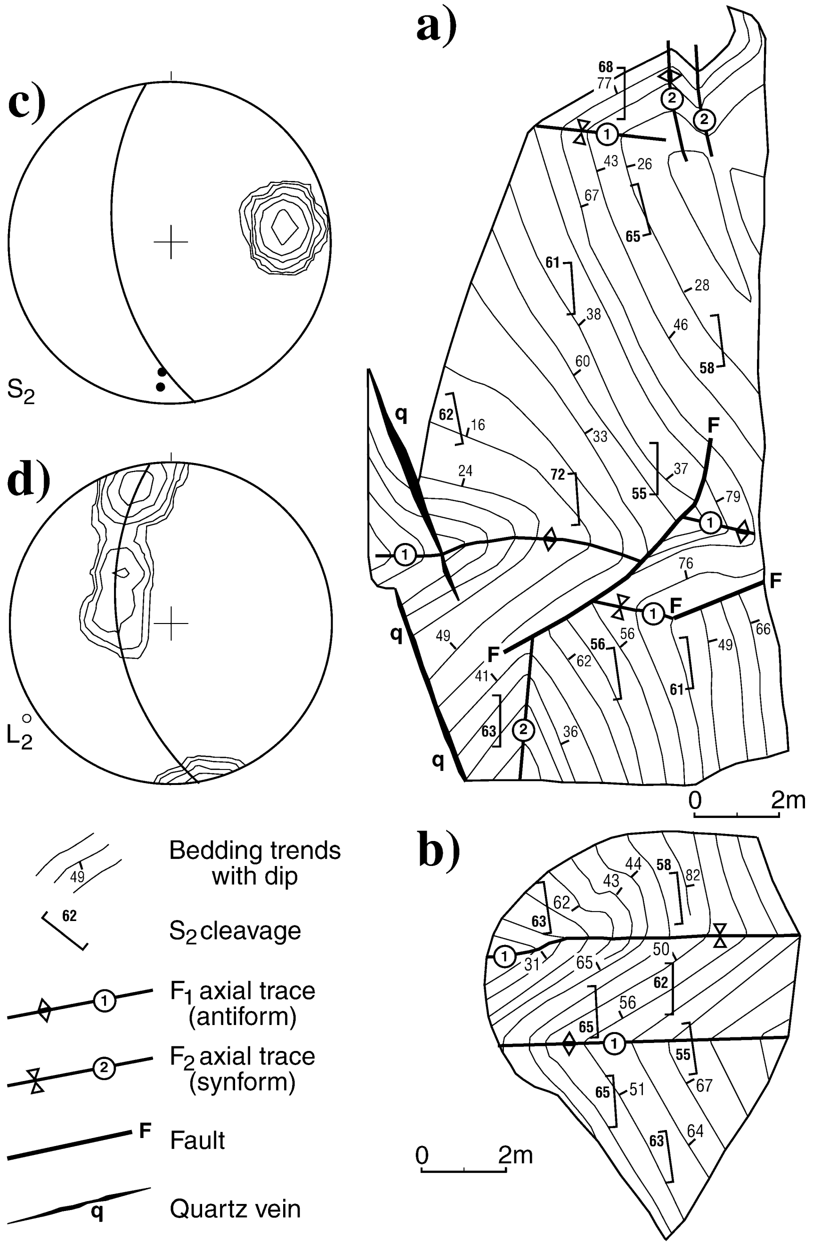

Fig. 8. Detailed maps of part of the rock platform at the southern end of Wimbie Beach showing the trend of beds in thin-bedded cherts of the Wagonga Formation (see Fig. 7 for location). East–west F_1 folds with no associated axial planar cleavage are refolded by north–south F_2 folds with a well-developed spaced axial planar dissolution cleavage. (a) Northern part of outcrop. (b) Southern part of outcrop. (c) Lower hemisphere equal area stereographic projection of 44 poles to S_2 contoured at 2, 4, 8, 16, 32 and 64% per 1% area (mean S_2 61°/262°) for both parts of the outcrop. Two points are poles to axial planes of F_1. (d) Lower hemisphere equal area stereographic projection of 39 intersection lineations between bedding and S_2 contoured at 2, 4, 8, 16 and 32% per 1% area (distributed along great circle 63°/260°) for both parts of the outcrop.

coastline we have been unable to convincingly identify any cleavage or even any fractures in chert in the cores and limbs of the early folds. In contrast the younger more intense deformation has developed a widespread cleavage in all rock types including siliceous rocks of the Wagonga Formation. We relate the lack of cleavage and fracturing to a shallow depth of burial and a relatively unlithified state of the Wagonga Formation during the early folding episode. As well these structures have not been identified in the stratigraphically lower Adaminaby Group. We therefore suspect that these folds are related to superficial downslope movement.

4.2. Deformation of soft sediments

Within the parts of the Adaminaby Group the alternating sandstone and mudstone contain abundant evidence of early soft-sediment disruption (Fig. 9). The most obvious features are delicate flame-like injections of mudstone at the upper and lower contacts of sandstone beds (Fig. 9a). Many of the

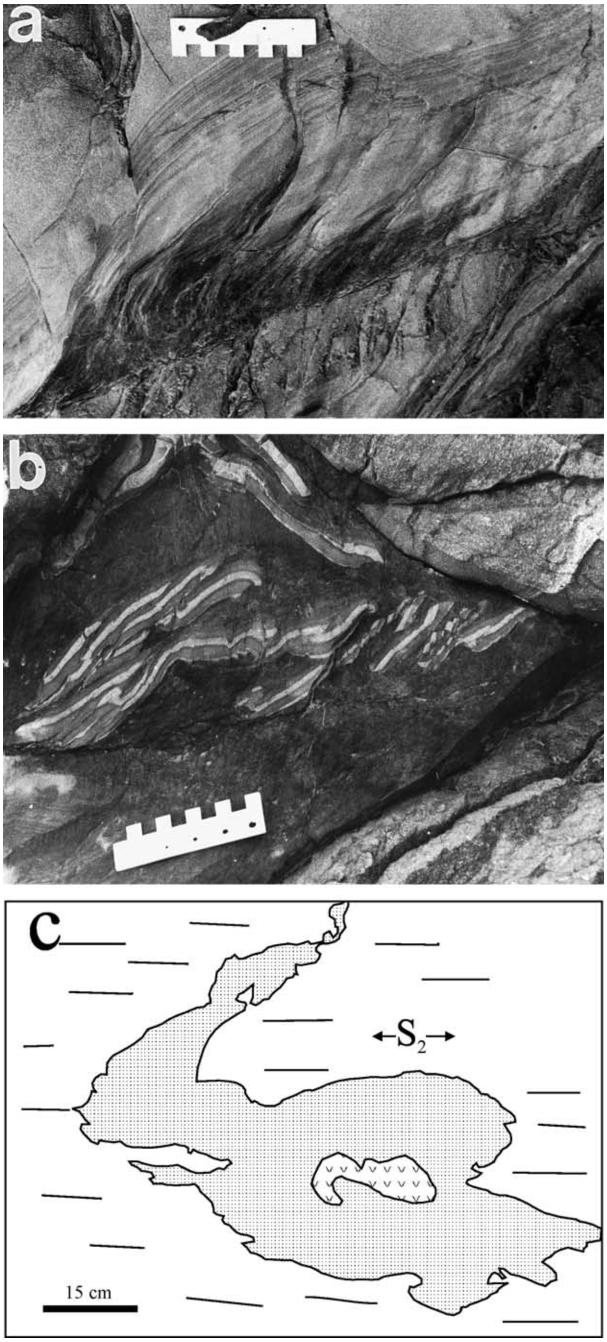

Fig. 9. (a) Mudstone injection features at a mudstone–sandstone contact in the Adaminaby Group, Burrewarra Point. Bar scale is 10 cm long. (b) Small-scale duplex developed in thin beds overlain by a thicker more coherent bed of sandstone, Adaminaby Group, south side of Burrewarra Point. (c) Sketch from a photograph of an irregular mass of clayey basaltic breccia occurring in slaty mélange of the Bogolo Formation, headland north of Malua Bay.

sandstone beds have also been disrupted resulting in lenticular beds with common pinch-out of sandstone into mudstone. At a larger scale all the thicker competent beds (up to 3 m thick) are discontinuous and can be traced no more than 20 m in the more disrupted quartz turbidites. Bed disruption has also been achieved by numerous delicate faults with relatively small displacements and thin gouge zones that most likely developed in relatively unconsolidated sediment (Fig. 9b). Thin fine sandstone layers in mudstone form duplexes in between thicker sandstone beds.

4.3. Early mélange fabrics

Locally a well-developed layering is evident in the mélange matrix and encloses lenticular fragments of competent rock types (Fig. 6d). The layering appears as a colour variation in the mudstone matrix but trains of extended fragments of sandstone indicate that much of the broken nature of the mélange developed early in the deformation history. Elsewhere only lenticular fragments in the mélange occur at a high-angle to the regional S_2 cleavage and are considered a relict of the early layering (Fig. 6e). Microstructural observations are consistent with early disruption of beds as quartz grains in the attenuated parts of quartz sandstone phacoids lack undulose extinction and imply that at the grain scale boudinage formed by a grain-boundary sliding mechanism. Thus flattening and formation of phacoids was probably early in the deformation history while the sandstones were still not completely lithified (Miller and Gray, 1996, fig. 7e). The early layering is folded about steeply to moderately west-plunging folds with axial planar regional S_2 cleavage indicating that the layering was steeply dipping prior to the regional deformation.

4.4. Early diapirs

The intensity of regional deformation has severely modified primary relationships between mélanges of the Bogolo Formation and surrounding rocks and between the elliptical masses, irregular pods and lenses of basalt, and rarely associated limestone amongst the bedded quartz turbidites of the Adaminaby Group. The distribution of the Bogolo Formation south of Batemans Bay forms many zones, the largest of which is up to 500 m in width and the narrowest of which is 5 m across (Figs. 4, 5 and 7). These units cross-cut the overall stratigraphic succession (Figs. 5, 7 and 10).

4.5. Early faults

Across a southern transect of the study area the Adaminaby Group is repeated in three main fault slices with the base of the unit exposed at Melville Point (Fig. 3c) and at Barlings Island (Fig. 5). Further east the Adaminaby Group is repeated at Burrewarra Point (Fig. 5) and this slice is found further north at Pretty Point (Fig. 10). These three fault slices represent major repetition of the stratigraphic succession that is related to early imbrication in the lower subduction complex setting (see below).

5. Regional deformation of the subduction complex

Regional deformation in the subduction complex rocks has formed abundant northerly trending folds, associated

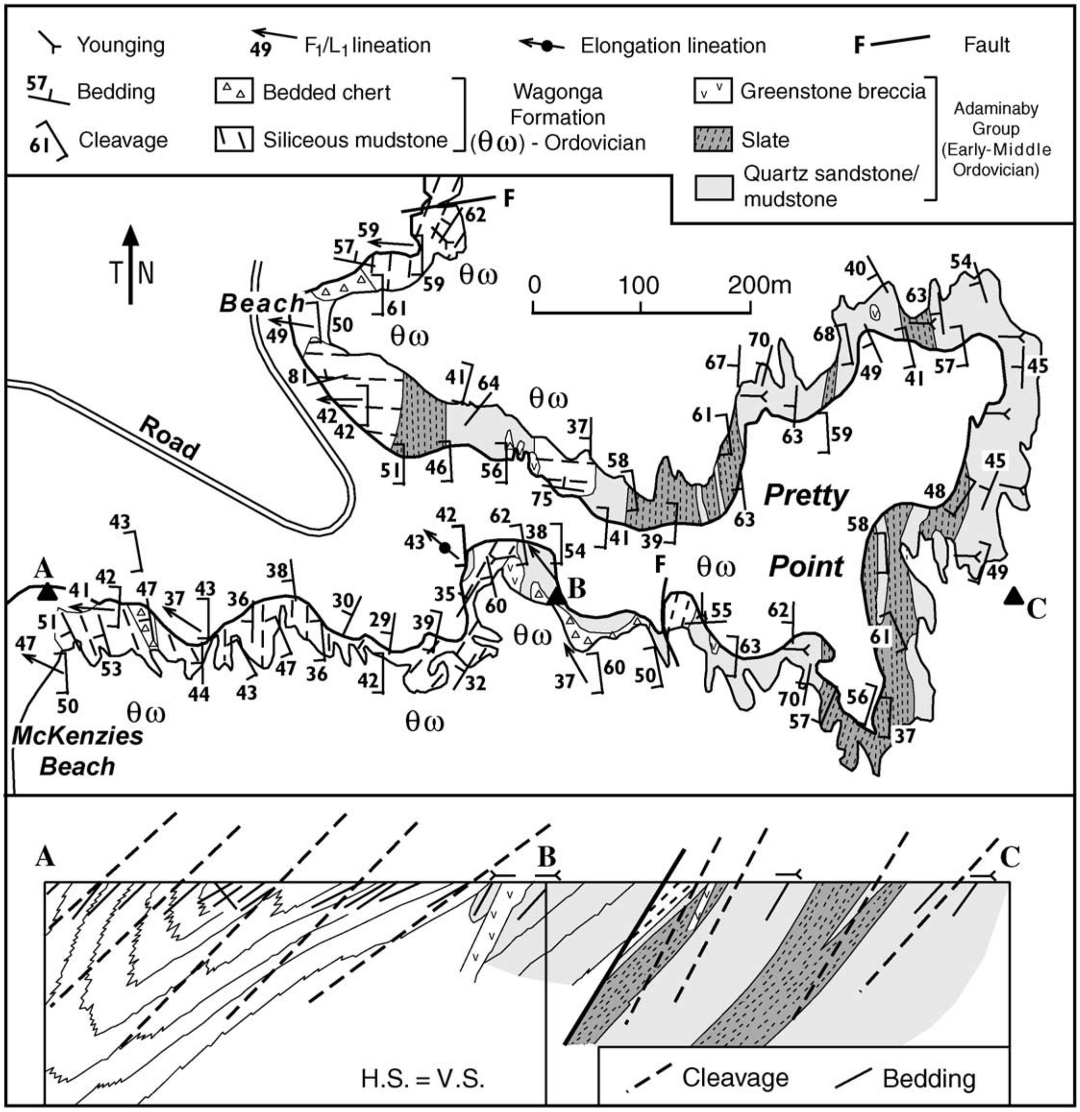

Fig. 10. Detailed map of Pretty Point headland and cross-section. Note that the succession in the Adaminaby Group is younging mainly to the west and is overlain by the more intensely folded Wagonga Formation.

axial planar cleavage and faults, especially along lithological contacts. Folds are particularly abundant in the chert and black siliceous mudstone of the Wagonga Formation and are less common in the Adaminaby Group and are only rarely found in the Bogolo Formation. In parts of the Wagonga Formation F_2 folds occur every 20–50 cm across strike resulting in intensely folded sections that locally display 80% fold shortening (Fig. 11). Folds are tight to locally isoclinal and many are asymmetric, typically with thinning of overturned eastern limbs indicating tectonic transport to the east. Complex dome-and-basin interference fold patterns formed by overprinting of F_1 folds (Fig. 8). In the Adaminaby Group, where F_1 folds are absent, most of the strata are younging and dipping moderately to steeply to the west indicating an overall eastward vergence (Figs. 4, 5 and 10).

Throughout the study area a spaced to slaty cleavage (S_2) is developed in all rock types and is typically dipping at 50–70° to the west (Figs. 4, 5 and 10). In the mélange matrix the cleavage forms a well-developed fine-grained white mica fabric with seams of insoluble residue formed by diffusion transfer (Offler et al., 1998; Fergusson and Phillips, 2001). In sandstone and chert the cleavage is spaced and has formed by dissolution. Within the mélange many phacoids show a well developed steeply pitching to the north down-dip elongation (Fig. 4). In many exposures in the Bogolo Formation, the elongation in S_2 is much more marked than flattening of phacoids in the S_2 plane. Rare pressure fringes developed on pyrites indicate that the phacoids are aligned in a stretching direction within the S_2 cleavage. Nevertheless in some outcrops, such as on the south side of Burrewarra Point (Fig. 5; 100 m east of J′), no elongation occurs within phacoids that are strongly flattened within S_2 (Fig. 6c). Lenticular mélange is also developed in some of the bedded

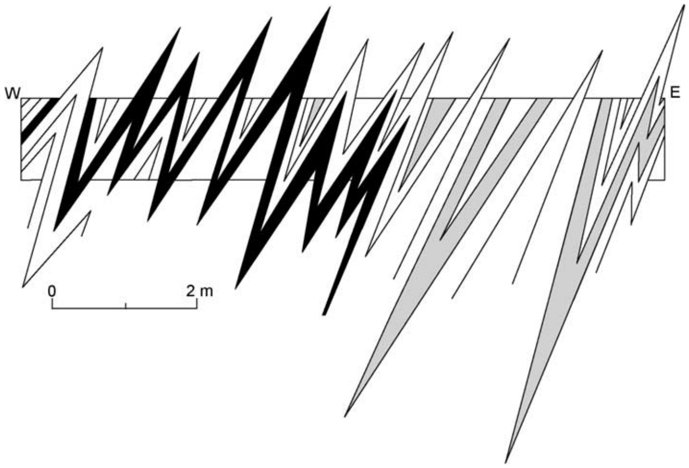

Fig. 11. Intensely folded representative section from the Wagonga Formation from the western side of Long Nose Point (see Fig. 5 for location). The folds alone indicate shortening in excess of 80%.

cherts where disruption has proceeded to the point where beds have been converted into lenticles aligned parallel to a spaced cleavage (S_2) in intervening mudstone. Stylolitic seams developed along the cleavage have at least locally developed the lenticular fabric.

Miller and Gray (1996) documented microstructures in the Bogolo Formation that record the complex strain history of the mélange with evidence of boudinage, reorientation, flattening and elongation of fragments in the matrix and have been confirmed in the study area south of Batemans Bay. One difference is that most of the elongate pods in the Narooma area are gently plunging to the north-northwest with some steeply pitching (Miller and Gray 1996, fig. 9) similar in orientation to those south of Batemans Bay. While strain associated with the regional deformation has enhanced the elongation lineation in the mélange it is clear that much of the initial fragmentation in the mélange predated this deformation (see above). Many fragments in the Bogolo Formation show symmetrical flattened shapes within the S_2 cleavage plane; but asymmetric boudinage is developed with most indicating a west over east sense of asymmetry (Fig. 6f). This is consistent with the sense of asymmetry of folds in the Wagonga Formation. Small delicate faults along the S_2 cleavage with mainly thrust offsets are abundant. Larger faults are developed along lithological contacts and within rock units throughout the complex. These structures have zones of brecciation, intense disruption of bedding and broken early quartz veins up to 15 m in width. They are typically steeply to moderately steeply dipping to the west (Fig. 5b) and contain mainly down-dip striations and quartz fibres. In many faults, kinking of S_2 cleavage is common indicating late movements and dilation across many of the fault planes. The overall structure is an imbricate stack resulting in repetition within various rock units across the complex (Fig. 5b).

Regional deformation is post-dated by abundant kinks, weak to locally strong crenulation cleavages. A zone 300 m wide occurs along the southern side of Burrewarra Point where widespread northwest-plunging folds and faults affect the S_2 cleavage (Fig. 5).

6. Discussion

6.1. Diapirism and early deformation in the Batemans Bay subduction complex

Studies of the emergent parts of some subduction complexes along with deep-sea drilling, seismic reflection profiles and side-scan radar of deep-sea inner trench slopes have shown that widespread mud diapirism is associated with deformation and accretion of sediments (Westbrook and Smith, 1983; Williams et al., 1984; Barber et al., 1986; Barber and Brown, 1988; Robertson et al., 1996). Nevertheless, many analyses of mélanges in subduction complex settings have concluded that block-in-matrix fabrics are the result of tectonic disruption along fault and shear zones, particularly along the major décollement at the base of the subduction complex (Cowan, 1985; Fisher and Byrne, 1992; Kusky and Bradley, 1999). The Bogolo Formation south of Batemans Bay forms a series of discontinuous strips that occur within the Wagonga Formation and at the margins of the Adaminaby Group and are unrelated to imbricate thrust sheets within the subduction complex (Figs. 4, 5 and 7). The pattern is considered to reflect early mud diapirs that have either intruded along early faults (Fig. 12) or have been subsequently flattened in the later regional deformation. All contacts of the Bogolo Formation where exposed are presently faulted, obscuring any local intrusive relations. Although the anastomosing pattern of Bogolo Formation along the coastal outcrops could be interpreted as a set of thickened shear zones (Moore and Byrne, 1987) this explanation cannot account for the abundance of quartz sandstone fragments in all parts of the Bogolo Formation even where it is distant from slices of the Adaminaby Group within the Wagonga Formation. If the Bogolo Formation

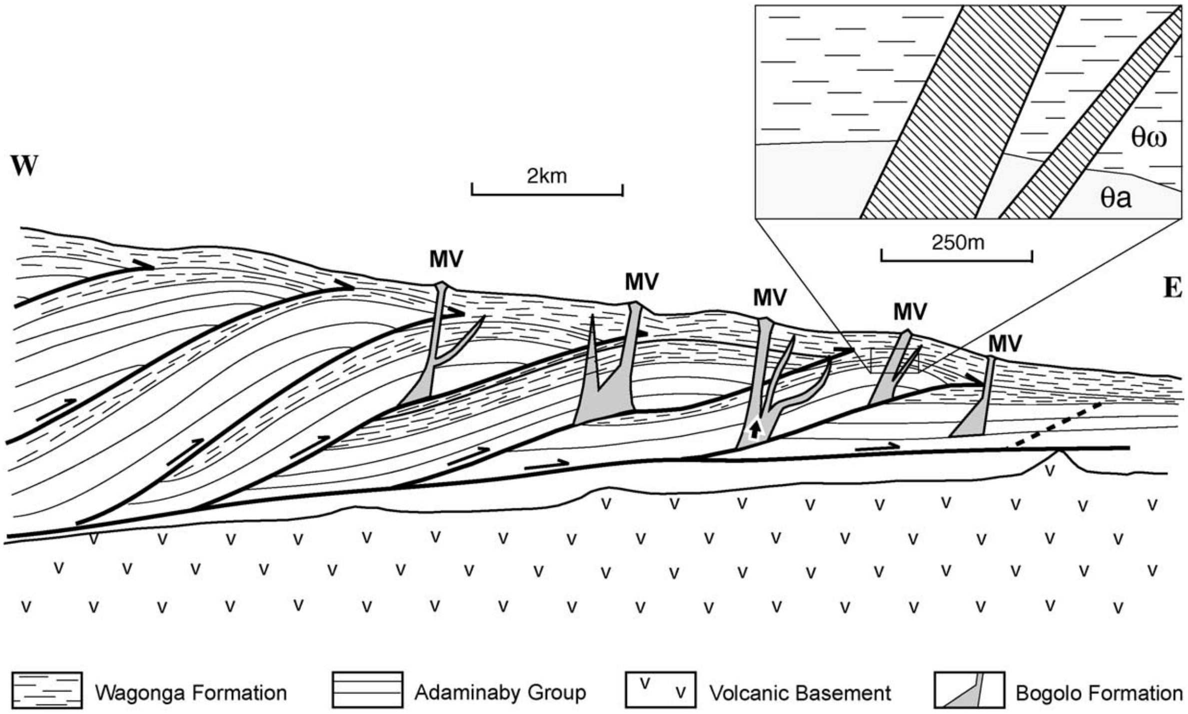

Fig. 12. Model for the development of the subduction complex in the Batemans Bay region with imbrication of the abyssal plain Adaminaby Group turbidites (θa in inset) and overlying abyssal, axial trench and lower slope Wagonga Formation (θw in inset) accompanied by mud diapirism to form mud volcanoes in the lower trench-slope and trench. Conduits to the mud volcanoes (MV) now form the Bogolo Formation (arrow indicates direction of upward flow in one diapir). Subsequent regional deformation has formed the intense F_2 fold event with substantial structural thickening of the earlier formed subduction complex.

always represented a thickened shear zone then many of the fragments should be locally derived from the neighbouring rock units.

Widespread mud injection features and initial disruption of sandstone layers indicate that unconsolidated, or partly consolidated, sediments were affected by deformation. These features are consistent with mobilisation of mud and mud diapirism being active during the accretion of unconsolidated sediments to the subduction complex. Can the Bogolo Formation be explained as a unit of olistostromes and muddy debris flows? Those parts of the Bogolo Formation that consist of abundant relatively small and angular clasts have been cited as having formed by this mechanism (Jenkins et al., 1982; Miller and Gray, 1996). Regional considerations are difficult to reconcile with any sedimentary origin for the Bogolo Formation. The dominance of quartz sandstone fragments in the Bogolo Formation indicates that it has been largely derived from the quartz turbidite succession of the Adaminaby Group. The Adaminaby Group and its equivalents are widely mapped throughout the Lachlan Fold Belt and locally contain mélanges in zones up to tens of metres across that have been mapped along fault zones (Fergusson and VandenBerg, 1990). Apart from the Wonnangatta Line (Fig. 1; Fergusson, 1987), in eastern Victoria 350 km to the southwest of the study area, mud-matrix mélange with fragments of quartz sandstone and chert similar to those at Narooma and Batemans Bay have not been identified in the Ordovician quartz turbidite succession. Evidence of syn-depositional slumps and soft sediment deformation abounds in this Ordovician succession yet olistostromes similar to those proposed for the Bogolo Formation have not been identified (Fenton et al., 1982).

The initial shape of the mud diapir as a pipe-like feature with mud injecting and invading neighbouring rock units, the radial orientation of foliation within the diapir and variations in the shapes of clasts, have been cited as evidence for mud diapirism (Williams et al., 1984; Orange, 1990). These features will only be preserved if the early history of the subduction complex can be somehow quarantined from later regional deformation. These criteria are less easily applied to ancient uplifted subduction complexes where significant regional strain has modified and distorted the early fabrics and clast shapes. The distribution of rock units south of Batemans Bay is now largely distorted by the regional deformation resulting in strong internal folding and cleavage development in rock units from west to east across the study area (Figs. 5, 10 and 11).

One of the most puzzling features of the coastal exposures is the distribution of basalts. These rocks commonly contain clay-rich rims and are all highly vesicular. They are mainly found either as fragments in either the Bogolo Formation (Fig. 9c) or as pods and lenticular masses at different levels in the Adaminaby Group and not found at the base of the unit as observed in uplifted subduction complexes and at Melville Point (Fig. 4). Volcanic rocks of any type are not found in the Adaminaby Group from outside the subduction complex (VandenBerg and Stewart, 1992). These field relationships are consistent with diapirism; alteration of the basalt rims resulted in lower density clay-enriched rinds that enabled overall lower density blocks to be diapirically emplaced into the Adaminaby Group. Subsequent mobilisation of parts of the Adaminaby Group in diapirs accounts for the widespread occurrence of vesicular greenstone fragments in the Bogolo Formation. Some of these basaltic breccias are associated with Cambrian limestone and therefore too old to have formed as syn-sedimentary intrusive hyaloclastites/pepperites associated with mud diapirism as the mudstone is stratigraphically much younger than the mafic volcanism.

6.2. Comparison with the Bogolo Formation at Narooma

The structure documented by Wilson (1968) and Miller and Gray (1996, 1997) at Narooma is an anticlinorium cored by the Bogolo Formation with structurally overlying Late Cambrian to Late Ordovician Wagonga Formation and in turn structurally overlain by Early to Middle Ordovician Adaminaby Group. Miller and Gray (1996) interpreted the chert–turbidite contact as a major detachment with the development of mélange and early cleavage. This structure had apparently been folded somehow to form the present Narooma anticlinorium. Miller and Gray (1997) documented tight folds in the bounding Ordovician quartz turbidites to the west and east of the Narooma anticlinorium that verge inwards rather than away from this structure and therefore are unrelated to the largescale structure. They attempted to explain these complicated vergence relationships by an inferred west-dipping shear zone on the eastern limb and an east-dipping shear zone on the western limb but recognised that the "problem of how the anticlinorium formed remains" (Miller and Gray, 1997, p. 247). Given that early fragmentation to form the Bogolo Formation predated all cleavage development and metamorphism it is conceivable that the mélange-cored Narooma anticlinorium developed as an early diapiric feature. The anticlinorium has been modified by complicated folding and shear zone development to form the present structure with axial planar slaty and crenulation cleavages (Miller and Gray, 1997, fig. 3). It is considered that it formed a mélange diapir (5 × 10 km) substantially larger than those inferred for the Batemans Bay region. The dimensions of this diapir are comparable with some of the surface features associated with mud diapirism such as mud volcanoes (10–20 km across) documented in deep-sea drilling from the Mediterranean Ridge (Robertson et al., 1996) and serpentine seamounts in the Izu–Bonin–Mariana forearc (Fryer et al., 1995).

6.3. Frontal accretion, underplating and structural thickening in the subduction complex

In many subduction complexes a disrupted trench-floor succession is repeated in part or full hundreds if not thousands of times in duplexes and imbricate fans (e.g. Kimura and Ludden, 1995). In contrast, in the Batemans Bay subduction complex the basal ocean floor basalt and overlying chert unit, as documented at Melville Point (Fig. 4; Powell, 1983; Bischoff and Prendergast, 1987), is largely missing. Instead the repetition involves a stratigraphic succession that formed part of a huge submarine fan complex that consisted of a lower turbidite succession (Adaminaby Group) and an upper chert–black mudstone unit (Wagonga Formation, Bendoc Group) that contrast to the normal accreted basalt–chert–mudstone–lithic sandstone slices (Fig. 3). Within the study area only two slices are developed and these have been substantially thickened by post-accretion regional deformation associated with upper anchizone metamorphism, intense folding and internal imbrication of the succession within the earlier fault slices (Figs. 5 and 10).

Distinction between frontal accretion and underplating is difficult in ancient subduction complexes as these processes are not separate but are transitional with each other from the frontal part to deeper levels under a subduction complex. Frontal accretion is likely to have been enhanced as a thick pre-existing sedimentary section (>2–3 km) entered the trench and was subsequently accreted (Westbrook et al., 1988). Additionally active thrusting involving uncompacted sedimentary sections is liable to have promoted gravitational instabilities and the development of mud diapirism in the frontal section of the subduction complex. In our model formation of the Bogolo Formation at Narooma is attributed to diapirism during early frontal accretion of water-enriched sediments that resulted in a giant diapir now represented by the Narooma anticlinorium (Fig. 2). Frontal accretion involving imbrication of the succession occurred at both Batemans Bay and Narooma and built up a substantial subduction complex.

Intense regional deformation has affected the early features along the south coast of New South Wales. At Narooma, Miller and Gray (1996) interpreted mélange developed along the chert–turbidite contact as a detachment along a major décollement zone at the base of the inferred subduction complex. They mapped the mylonitic fabric along this detachment as being transitional into a strong early cleavage (S^*) in the turbidites. At Bermagui the early cleavage was found to form at an angle to bedding and not a bedding-parallel fabric as had previously been assumed (Powell and Rickard, 1985). We consider that the detachment is probably an early structure formed during frontal accretion where the turbidite unit has been thrust over an oceanic basinal unit (the Wagonga Formation). Subsequently, intense cleavage development, tight folding and localised mélange has occurred along the shear zone during regional deformation of the subduction complex. At Bermagui this deformation was associated with localised higher anchizonal metamorphic conditions (Offler et al., 1998). From Narooma to Batemans Bay slightly lower grades of anchizonal metamorphism (IC values of 0.29–0.30) were demonstrated for the turbidite and chert units implying that they were all metamorphosed at similar depths at around 445 Ma (Offler et al., 1998). The younger constraints provided by the ^{40}Ar/^{39}Ar data from south of Batemans Bay (440–400 Ma) could be construed as evidence for older regional deformation at Bermagui (Fergusson and Phillips, 2001). Difficulties of inheritance and recoil encountered in these rocks require that more data is needed to assess the significance of these apparent differences in timing of regional deformation. Miller and Gray (1996) attributed deformation along the turbidite–chert contact to underplating but an alternative is that the complicated regional deformation is part of an end Ordovician to Early Silurian deformation that has been superimposed on the subduction complex as a result of changing plate motions. Subduction was active throughout the Ordovician and the timing of this deformation therefore occurred near the end of the accretionary episode and is consistent with a change of tectonics throughout the Lachlan Fold Belt in the Early Silurian (Powell, 1984).

7. Conclusions

Rather than demonstrating the importance of underplating during formation of a subduction complex (Miller and Gray 1996, 1997; Offler et al., 1998), we suggest that the Batemans Bay subduction complex illustrates the importance of processes of mud diapirism, soft sediment deformation and post-accretion deformation in the build-up of a subduction complex. In contrast to many subduction complexes the Batemans Bay subduction complex has formed by the accretion of a fining-upward succession. Widespread mud-matrix mélange in the complex is attributed to mud diapirism rather than either to the underplating of debris flow deposits or the development of a thickening shear zone along the basal décollement.

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