THE STRUCTURAL HISTORY OF THE LEMAY GROUP OF CENTRAL ALEXANDER ISLAND, ANTARCTIC PENINSULA

T. H. Tranter

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Abstract. The LeMay Group accretionary complex has a long, polyphase structural history. In central Alexander Island, the first deformational episode (D_1) is characterized by the widespread development of layer-parallel fabrics, stratal disruption in poorly lithified sediments, and accretion-related thrusting in a variety of rock types. The variation in D_1 can be interpreted in terms of the differing positions of lithological units within the developing complex. 'D_2' deformation cannot be correlated precisely throughout the area, and comprises two distinct structural styles. A belt of arcward-verging folds and arcward-directed thrusts can be attributed to the response of material already incorporated into the complex to continuing subduction-related stresses, and may be related to structures with a similar orientation in the fore-arc basin deposits to the east. Elsewhere, local areas of downward-facing strata of uncertain origin are developed. Later structures include widespread normal or oblique-slip faulting related to Cenozoic intra-arc extension and ?strike-slip movement, together with locally developed episodes of quartz veining, and regional folding.

The LeMay Group of central Alexander Island is interpreted as a mixture of arc-derived clastic units and allochthonous oceanic units accreted to the active margin. Changes in structural style are related to varying accretionary processes in different parts of the complex.

Introduction

Since at least Mesozoic times, the Antarctic Peninsula has been the site of magmatic activity associated with the eastward subduction of Pacific and proto-Pacific oceanic crust beneath the Antarctic Plate (Thomson and others, 1983; Storey and Garrett, 1985). During the earliest part of this subduction history, the area occupied by the present peninsula formed part of the Gondwanian continental margin, but prior to, during and following the break-up of the supercontinent which commenced in the Middle Jurassic (Barker and Griffiths, 1977), a magmatic arc related to continuing subduction became established. In recent tectonostratigraphic syntheses of the Antarctic Peninsula (e.g. Storey and Garrett, 1985), terranes corresponding to pre-Mesozoic basement, accretionary complex, fore-arc basin, magmatic arc and back-arc basin environments have been recognized.

Alexander Island is the largest island on the west coast ('fore-arc') of the Antarctic Peninsula and extends some 400 km between 68° 46′ S and 72° 41′ S (Fig. 1). The structural basement of the island consists of the LeMay Group, a thick sequence of variably metamorphosed and deformed sedimentary and extrusive igneous rocks (Edwards, 1980*a*; Burn, 1984). This is in faulted and unconformable contact (Edwards, 1980*b*) with the Fossil Bluff Formation of eastern Alexander Island, a thick sedimentary sequence of Late Jurassic–Early Cretaceous age deposited in a fore-arc basin setting (Taylor and others, 1979; Butterworth, 1985). Calc-alkaline plutonic and associated volcanic rocks of Tertiary age (Thomson and Pankhurst, 1983; Thomson and Burn, 1977) intrude and unconformably overlie the LeMay Group, and represent a westward migration of the magmatic arc during Tertiary time

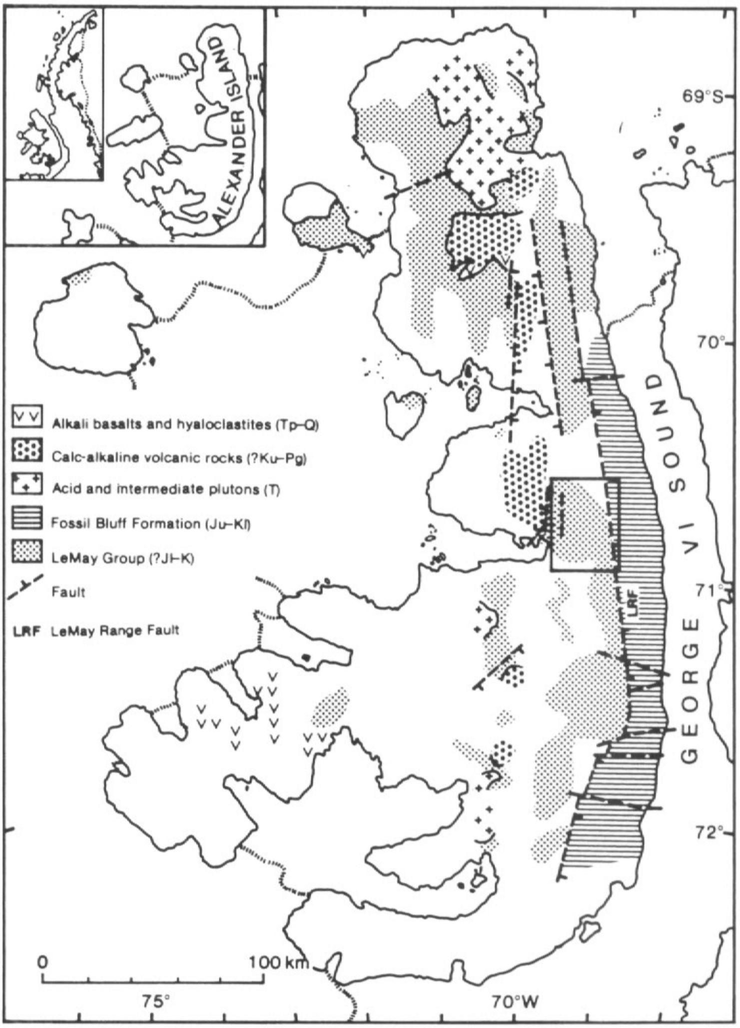

Fig. 1. Sketch geological map of Alexander Island. The area described in this paper is outlined.

(Saunders and others, 1982). Scattered exposures of late Tertiary alkaline volcanic rocks also unconformably overlie the LeMay Group (Burn and Thomson, 1981); these are related to Cenozoic extensional tectonism (Garrett and Storey, 1987).

The age of the LeMay Group is poorly constrained and based on sparse palaeontological and radiometric evidence. Dubious Carboniferous palynomorphs (Grikurov and Dibner, 1968) (the identification of which was strongly questioned by Schopf, 1973), an Early Jurassic (Sinemurian) macrofossil assemblage (Thomson and Tranter, 1986) and a ?mid-Cretaceous radiolarian assemblage (Burn, 1984) indicate a long depositional history. Grikurov and others (1967) reported K/Ar dates on biotite concentrates from central Alexander Island ranging from 102 to 161 Ma, and, although there is no direct indication in the literature whether the biotites were of detrital or metamorphic origin, these dates are thought to represent diagenetic, deformational or uplift-related events (Grikurov and others, 1967; Burn, 1984). A minimum age for part of the LeMay Group is provided by its unconformable contact with the Upper Jurassic Lower Cretaceous Fossil Bluff Formation in east central Alexander Island (Edwards, 1980*b*).

Structural History of the LeMay Group

Previous studies

Early aerial reconnaissance led King (1964) to interpret the rocks of central Alexander Island as strongly folded Cretaceous strata, analogous to the Fossil Bluff Formation to the east. Grikurov (1971), the first geologist to work on the LeMay Group, made general structural observations in central Alexander Island, and interpreted the major structure as a north-north-west-trending anticline with local folding. Reconnaissance mapping by BAS geologists, chiefly in northern and southern Alexander Island (Bell, 1973, 1974, 1975; Care, 1980) showed that parts of the LeMay Group have undergone a complex, polyphase structural history with up to three phases of folding.

The most comprehensive accounts of the structure of the LeMay Group are those of Edwards (1980*a*) and Burn (1984) in central and northern Alexander Island respectively. Both authors recognized four phases of deformation, although correlations drawn between geographically disparate areas were rather tentative, and the full development of all deformational phases in the same exposure was seen by neither author. Both Edwards and Burn interpreted the LeMay Group in terms of a general subduction–accretion model, although Burn highlighted some apparent inconsistencies, e.g. the lack of thrust-related deformation, and the widespread occurrence of westerly and south-westerly ('oceanward') dips in the LeMay Group. This is in contrast to the 'classic' accretionary complex model (e.g. Dickinson and Seely, 1979), in which landward dips and series of seaward-verging folds are developed.

Present study

Mapping by the author of part of the LeMay Group in central Alexander Island between 70° 41′ S and 70° 57′ S (Fig. 1) has allowed the delineation of four geographically, lithologically and structurally disparate units (Fig. 2).

(A) Conglomerate–sandstone–mudstone association of the eastern LeMay Range. This consists of resedimented conglomerate and sandstone units deposited from high-density sediment gravity flows interbedded with sandstone, siltstone and mudstone units representing turbidity-current deposits. Minor exposures of pebbly mudstones with isolated slump noses indicate local debris flows.

(B) Sandstone–mudstone association of parts of the western LeMay Range. This is composed almost exclusively of thin- to medium-bedded sandstones and mudstone of turbiditic origin, with only very minor conglomerates.

(C) Basalt–chert association of parts of the western LeMay Range. Non-vesicular pillow and massive lavas, interbedded with red and green radiolarian and non-radiolarian cherts, siltstones and mudstones crop out along a narrow belt in the western LeMay Range. They are in sedimentary and thrust contact with the clastic rocks of association B. They are thought to represent oceanic crustal material, although the presence of detrital grains in the interbedded sedimentary rocks indicates an incomplete isolation from a clastic source.

(D) Basalt–tuff association of the Lully Foothills (the Lully Foothills Formation

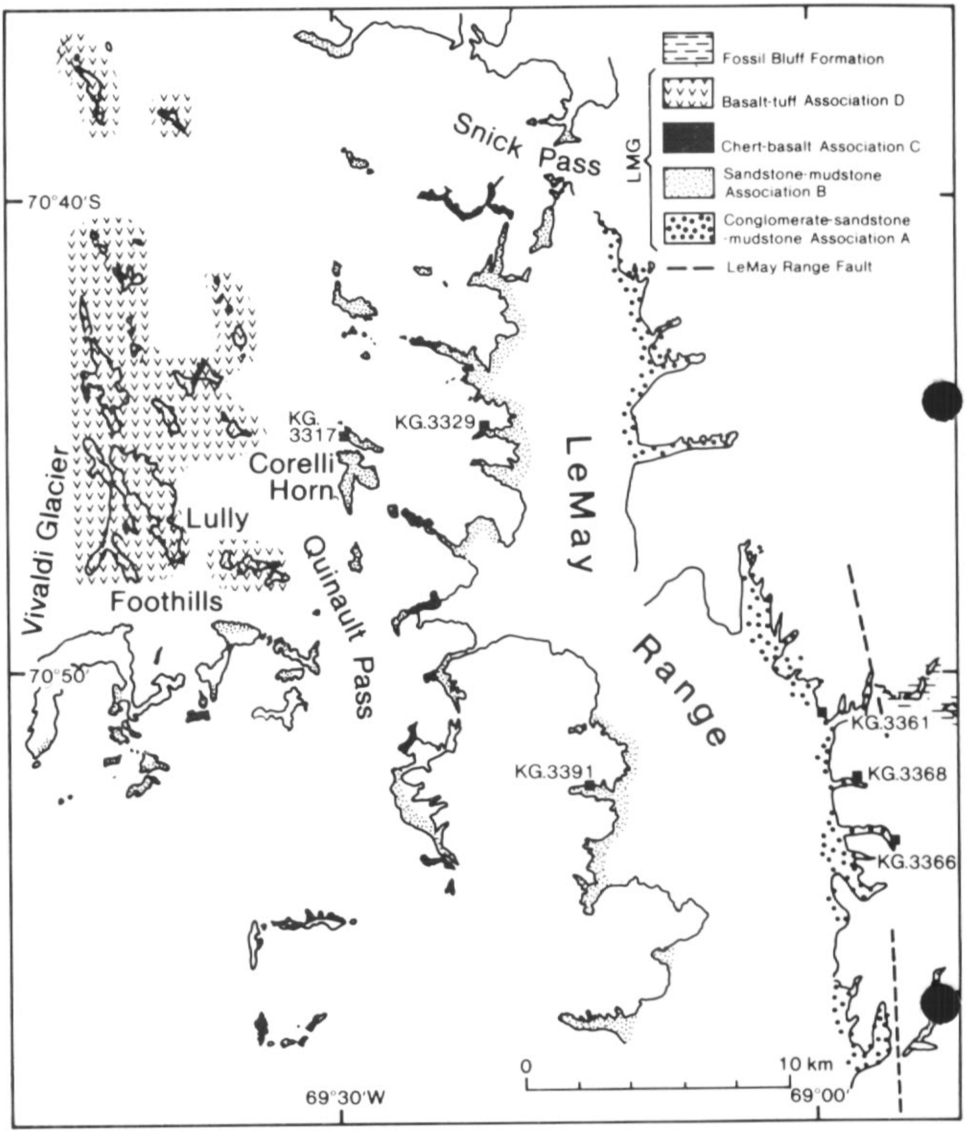

Fig. 2. Geological map of the LeMay Group of central Alexander Island, showing place names and geological station numbers mentioned in the text and figure captions.

of Burn, 1984). The Lully Foothills consist of a major block of vesicular basaltic pillow lavas and lava flows, with interbedded basaltic hyaloclastic breccias and rarely fossiliferous vitric, crystal and lithic tuffs (Thomson and Tranter, 1986). Volcanic bombs and the presence of plant remains in the fossil assemblage indicate nearby locally subaerial conditions.

D_1 *deformation*

An almost ubiquitous bedding-parallel or sub-parallel S_1 cleavage is present throughout the LeMay Group of central Alexander Island. It ranges from a hackly, shaly fabric in the thinly bedded parts of association A and parts of association B, to more strongly developed ductile and pressure solution fabrics in associations B, C and D.

In the clastic rocks of the eastern and western LeMay Range (associations A and B), S_1 cleavage development is accompanied by a widespread phase of stratal disruption and sediment mobilization. The disruption is confined to broad zones, above and below which laterally continuous undisrupted bedding is preserved. It is evident on all scales, from cliff faces (Fig. 3) to within individual sandstone or

Fig. 3. Large-scale D_1 stratal disruption of sandstone in mudstone. Station KG. 3366, eastern LeMay Range. Figure (arrowed) for scale.

siltstone beds (Fig. 4). Sandstone beds, which in the most highly disrupted areas generally lack sedimentary structures, show a complete gradation from pinch and swell through boudinage (Fig. 5) to blocks 'floating' in a matrix of cleaved mudstone and thinly bedded siltstone. Most commonly, the blocks are lenticular or tabular and are recognizable as the dismembered parts of a once continuous sandstone bed, but more isolated rhomboidal or rounded blocks also occur. The sizes of the bodies are highly variable, and they range in thickness from less than ten centimetres to more than a metre. Sandstone injection structures into mudstone occur at the margins of

Fig. 4. Small-scale D_1 stratal disruption of sandstone in mudstone. Station KG.3366, eastern LeMay Range. Hammer shaft is 35 cm in length.

some sandstone bodies. Where sedimentary structures are preserved, bedding within disrupted zones is broadly parallel to that within nearby undisrupted parts, but some large rhomboidal bodies lie discordantly to regional dip, suggesting syndeformational rotation. Rare calcite and quartz veins, approximately perpendicular to the long axes of sandstone bodies, show that brittle extension was locally important. S_1 cleavage is restricted to the finer-grained lithologies, and wraps around the margins of blocks in disrupted zones. Minor structures related to S_1 cleavage are rare in the eastern LeMay Range, although tight folds with axial-planar cleavage and inconsistent vergence are

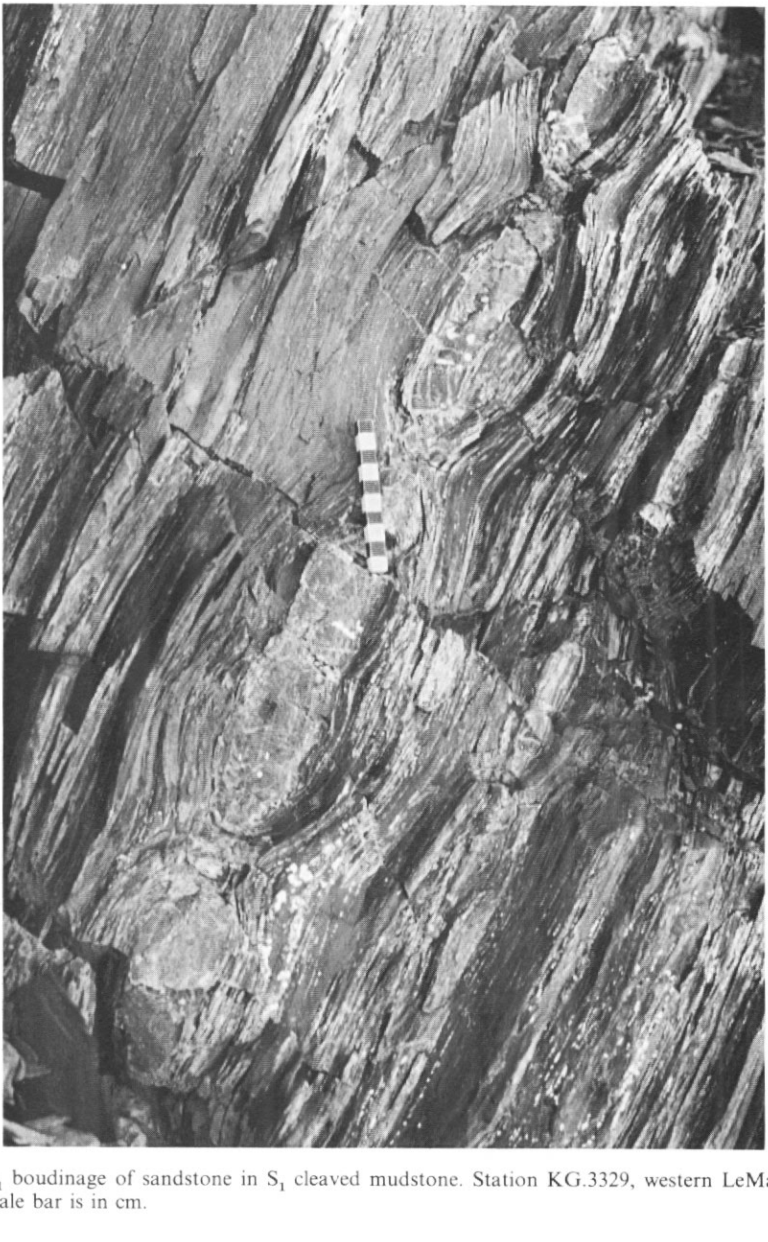

Fig. 5. D_1 boudinage of sandstone in S_1 cleaved mudstone. Station KG.3329, western LeMay Range. Scale bar is in cm.

present in places, and small-scale westerly directed thrusts are also developed in a few instances.

In the western LeMay Range, however, D_1 deformation is genetically related to a phase of north-westerly-directed thrusting (Figs 6a and b). In the Corelli Horn area, S_1 cleavage planes in rocks of association B are parallel to F_1 minor fold axial planes and to thrust planes. Bedding in the same area shows a wide scatter, possibly as a result of lateral thrust ramping, although field relationships are unclear. Some of the

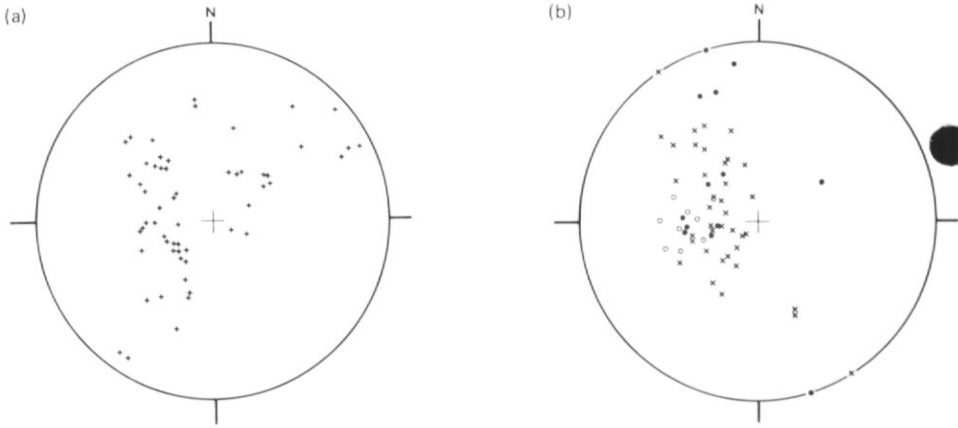

Fig. 6. Structural data, Corelli Horn area, western LeMay Range. Lower-hemisphere equal-area projection. (a) +, Poles to bedding near D_1 thrusts. (b) ×, Poles to S_1 cleavage near D_1 thrusts; ●, poles to axial planes of F_1 folds; ○, poles to D_1 thrust planes.

thrust planes are marked by thin (up to 1 cm) sheets of sandstone which pass directly into the sandstone beds above and below the thrust (Fig. 7). These represent unlithified sediment mobilized from adjacent beds during thrusting and introduced along the thrust plane.

Elsewhere in the western LeMay Range, westerly directed D_1 thrusting has emplaced clastic rocks of association B over the cherts and basalts of association C. The siliceous rocks have acted as décollement horizons and are strongly folded into westerly verging minor folds with axial planar S_1 cleavage. Chloritic cleaved skins are developed around pillows, and bedding-parallel pressure solution and ductile fabrics are common in semi-schistose greenschist facies equivalents of associations B and C in parts of the western LeMay Range.

In the eastern Lully Foothills, D_1 fabrics are well developed in an approximately north–south-orientated mélange zone at least 150 m wide, which forms a major tectonic boundary between the volcanic rocks of association D and the rocks to the east. The zone, which has been reorientated by later folding, consists of large numbers of inclusions of basaltic lava, sandstone and chert set in a matrix of very fine-grained red and green mudstone, phyllite and slate. The inclusions vary in size from a few mm (apparent in thin section) to several metres and in shape from disaggregated pillows to rhomboidal blocks and tabular bodies.

Deformation of the inclusions is variable. The competent igneous lithologies have remained internally undeformed, with the preservation of sub-spherical vesicles and microscopic volcanic textures. Extension in these competent blocks is accommodated by brittle fracture and the development of quartz- and calcite-filled tension gashes perpendicular to inclusion surfaces. Small inclusions of sedimentary rocks are devoid

Fig. 7. Detail of D_1 thrust plane in interbedded sandstone and mudstone. Station KG.3317, western LeMay Range. Scale bar is in cm.

of primary structures, probably as a result of grain boundary sliding, but in the cores of the largest inclusions (several metres in diameter) sedimentary structures are preserved, and evidence of soft-sediment extensional deformation is provided by synsedimentary faulting. S_1 cleavage wraps around the inclusions and shows evidence of ductile strain. Some small inclusions within the cleaved matrix are reduced to aligned trails of fragments, and in places show tails and pressure shadows. Indicators of shear sense are rarely apparent, but where identified are consistent with an original top to the west transport direction.

Elsewhere in the Lully Foothills, S_1 cleavage is broadly parallel to lithological boundaries but is strongly influenced by variations in rock type. It is absent from massive igneous lithologies, and some sedimentary rocks between such igneous bodies are almost totally undeformed.

The D_1 structures and fabrics in central Alexander Island represent deformation over a range of depths and degrees of lithification. In the clastic rocks of the eastern LeMay Range, the widespread zones of stratal disruption, eradication of sedimentary structures and apparently contemporaneous cleavage development in rocks of low metamorphic grade (rarely up to prehnite-pumpellyite) suggest disruption of poorly lithified sediments, with grain boundary sliding as the dominant process. This implies deformation of material at the sediment–water interface (slumping) or at shallow depths of burial. The paucity of pebbly mudstones, slump scars and features associated with glide block emplacement (e.g. Naylor, 1982) indicates that slumping was unlikely to have been a major deformational process. However, the confinement of stratal disruption to zones bounded by undeformed beds, the development of rare minor folds and westerly directed thrusts and the syndeformational rotation of sandstone blocks out of parallelism with bedding are all consistent with disruption due to a westerly directed shear couple or to extension in near-surface, poorly lithified material. Similar features, attributed to a combination of interstratal shearing with some submarine sliding, have been described from the Coastal Belt of the Franciscan of northern California (Kleist, 1974; Bachmann, 1982). The local occurrence of brittle deformation (e.g. veining and faulting) indicates local zones of higher strain, strain rate or deformation of more deeply buried, de-watered and lithified material, in which solution-transfer processes may also have been operative, similar to the transitional sequence of deformational mechanisms described by Knipe and Needham (1986) from the Southern Uplands accretionary complex.

In the western LeMay Range, a history of westerly directed D_1 thrusting is again apparent. In parts this is a high-level deformational process in poorly lithified material (association B) resulting in sediment mobilization and boudinage during thrusting, but in the basalt–chert association C, sub-surface conditions of deformation are inferred from the higher metamorphic grade (up to greenschist facies) and the stronger development of ductile S_1 fabrics. The two units are in thrusted contact, and D_1 deformation as currently exposed in the western LeMay Range is the product of westerly directed thrusting at two distinct structural levels.

The D_1 mélange zone of the eastern Lully Foothills is a major structural boundary within the LeMay Group, across which there is a marked change in rock type. However, temporal relationships of cleavage development to the evolution of the zone are equivocal. Soft-sediment extensional structures, preserved in the cores of the largest inclusions, indicate deformation of near-surface, poorly lithified material, whereas mechanical granulation, mineral growth and ductile deformation associated with S_1 cleavage development in the matrix indicate 'sub-surface' conditions of cleavage development. However, the preservation of original textures within inclusions must mean that bulk strain remained comparatively small during cleavage development. The mélange zone probably thus reflects a long history of development, incorporating blocks of material from a variety of structural levels, with the gradual imposition of a cleavage fabric and new mineral growth concomitant with tectonic transport to depth.

D_2 deformation

Deformation of D_1 fabrics and structures is widespread, but shows marked variation in style and orientation throughout the area. With a lack of stratigraphic control and of knowledge of the relative timing of structural development it is not possible to correlate 'D_2' structures precisely between areas.

In the rocks of association A in the eastern LeMay Range, bedding and D_1 structures are folded into major eastward-verging F_2 folds and disrupted by eastward-directed D_2 thrusts. Major F_2 folds are seen in cliff section (Tranter, 1986, fig. 4) or their presence may be inferred from changes in younging of strata and in the vergence of F_2 minor folds, which are common in the thinly bedded parts of the sequence. Axial-planar cleavage related to F_2 folds is rare, although crenulation fabrics of S_1 cleavage in mudstones on a mm–cm scale are locally developed. Competence contrasts between different lithologies has strongly influenced the style of folding, with mudstone beds acting as décollement horizons producing strongly disharmonic folds (Fig. 8).

The axial planes show some scatter, but most dip gently to moderately to the west (Fig. 9a) and have hinges plunging gently to moderately to the south–south-east or north–north-west (Fig. 9b).

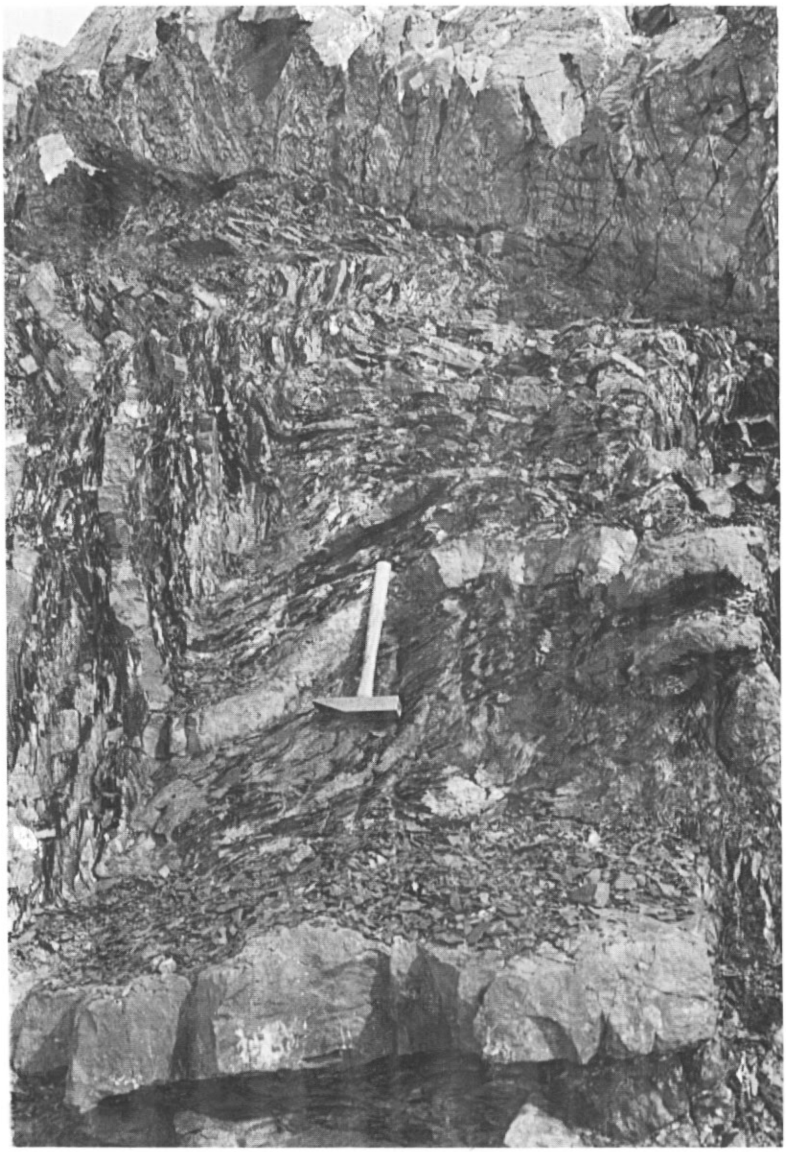

Fig. 8. Disharmonic F_2 folding in thinly interbedded sandstone and mudstone between thicker sandstone beds. Station KG.3368, eastern LeMay Range. Hammer shaft is 35 cm in length.

Major D_2 thrusts were only rarely observed in cliff exposures (Fig. 10) and indicate eastward movement of the hanging wall, and minor small-scale thrusts indicate both easterly and westerly transport directions. Minor extensional ?D_2 faults truncating bedding and S_1 cleavage, and with blocks of sandstone dragged into alignment along the fault plane, downthrow to the north-west.

In the western LeMay Range, structures deforming D_1 fabrics are highly variable in orientation in different areas and correlation cannot be confirmed. At Snick Pass,

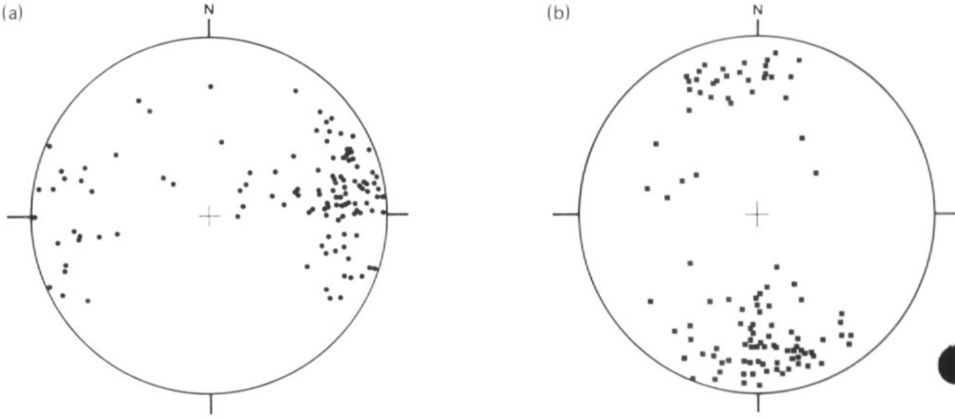

Fig. 9. F_2 structural data, eastern LeMay Range. Lower-hemisphere equal-area projection. (a) ●, Poles to axial planes of F_2 minor folds. (b) ■, Plunges of F_2 minor fold axes.

where schistose and semi-schistose equivalents of associations B and C crop out, S_1 cleavage fabrics delineate a major syncline, plunging gently to the south-east (Fig. 11a). Minor F_2 fold-axial planes show a wide scatter (Fig. 11b), but their axes, together with mineral lineations on S_1 cleavage planes and mullions on the base of sandstone beds, show a consistent plunge to the south-east (Fig. 11c).

To the south, D_2 deformation in the western LeMay Range has led to the development of local areas of downward-facing strata. Closely spaced S_2 fabrics are axial planar to faulted tight or isoclinal F_2 folds (Fig. 12a). Fold closures are rarely seen and are inferred from changes in younging directions and rare minor fold vergence, but a faulted synclinal fold plunges moderately steeply to the south-east (Fig. 12b). Calculated bedding/cleavage intersection lineations are highly variable. Areas of downward-facing strata have been reported from elsewhere in the LeMay Group of Alexander Island. Burn (1984) interpreted areas of downward-facing 'F_2' folds in northern Alexander Island as resulting from the refolding of the inverted limbs of recumbent 'F_1' folds, or by the refolding of 'F_2' axial planes by 'F_3' folds. However, no evidence for the existence of such large-scale 'F_1' structures was presented for northern Alexander Island, and neither were any such structures identified in central Alexander Island. There is no evidence to suggest that the downward-facing beds are due to the folding of beds inverted during soft-sediment slumping, and other possible mechanisms capable of generating downward-facing structures, invoking complexities due to stacking and rotation of a developing duplex sequence or backthrusting (e.g. Boyer and Elliott, 1982; Knipe and Needham, 1986), seem untenable as there is no evidence for a major thrusting episode related to D_2 deformation in the western LeMay Range. An alternative explanation for the local development of downward-facing strata is that it results from the re-orientation of folds with non-linear hinges (Nell and Storey, in press; fig. 3). This may occur with steepening of the axial planes of steeply plunging folds, where small variations in fold-hinge orientation can lead to facing changes. Although evidence for steeply plunging folds is restricted to the moderately steeply plunging syncline described above (Fig. 12b), zones of steeply plunging folds have been identified farther to the north in Alexander Island and may result from a strike-slip tectonic regime (Nell and Storey, in press). It is therefore possible that the D_2 structures in the western LeMay Range represent a localized zone of similar strike-slip movement.

Fig. 10. Eastward-directed D_2 thrust. Station KG.3361, eastern LeMay Range. Cliff is approximately 250 m high.

Later structures

All parts of the LeMay Group of central Alexander Island are cut by a variety of faults and fractures and warped by later folding. Many of these sets of structures are local and regionally unimportant, but dominant trends within some sets of structures can be recognized. In most cases it is not possible to establish the relative chronology of these late structural events, as cross-cutting relationships are contradictory.

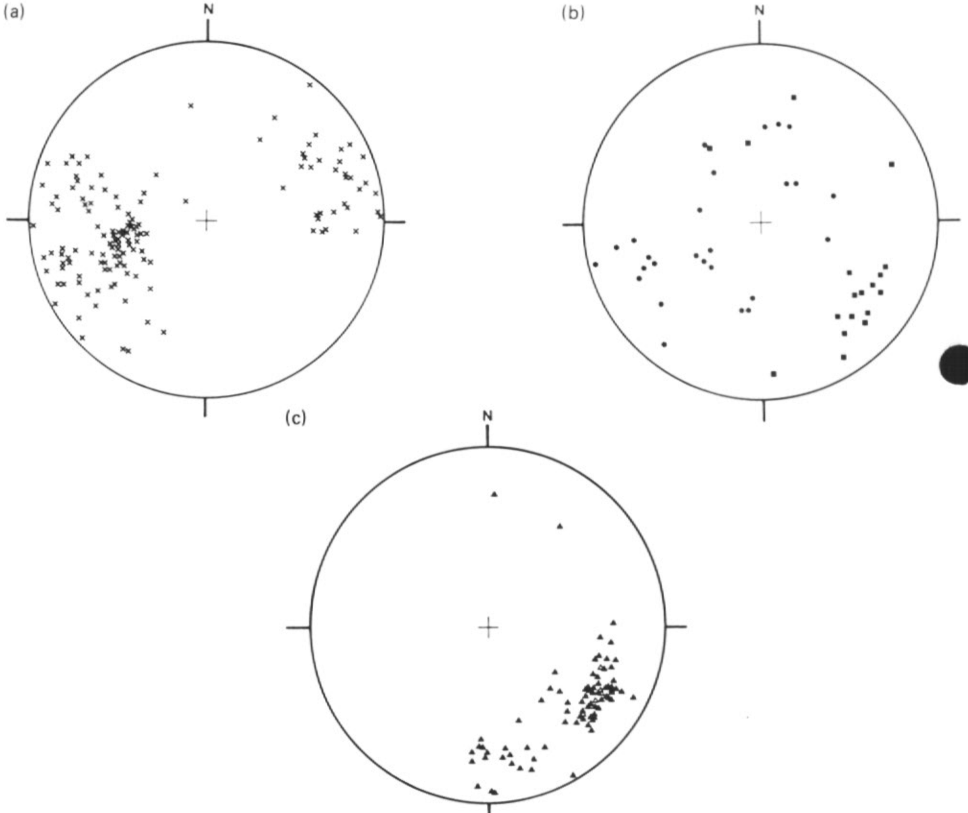

Fig. 11. F_2 structural data, Snick Pass area, north-western LeMay Range. Lower-hemisphere equal-area projection. (a) ×, poles to S_1 cleavage. (b) ●, poles to axial planes of F_2 minor folds; ■, plunges of F_2 minor fold axes. (c) ▲, plunges of mineral lineations on S_1 cleavage surfaces; △, plunges of mullions.

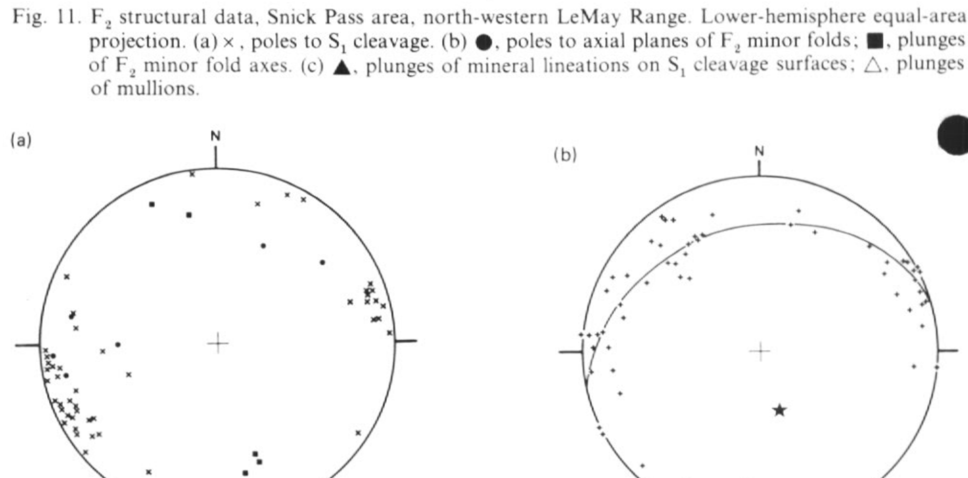

Fig. 12. Structural data, KG.3391, western LeMay Range. Lower-hemisphere equal-area projection. (a) ×, poles to S_2 cleavage; ●, poles to axial planes of F_2 minor folds; ■, plunges of F_2 minor fold axes. (b) F_2 syncline, eastern end of KG.3391. +, poles to bedding and S_1 cleavage. ★, estimated fold axis of F_2 syncline.

(i) *Faulting*. High-angle faulting, striking north–south to north-east–south-west, occurs throughout the area. In parts of the eastern LeMay Range, lineated fracture surfaces in sandstones and conglomerates indicate dip-slip movement to the east, but in other parts of the eastern LeMay Range, fracture surfaces show a high degree of scatter and indicate both dip-slip and oblique-slip movements. Similarly in the western LeMay Range, approximately north–south-striking faults with a net normal sense of displacement can be inferred from the offset of a distinctive red chert band in association C, although where slickenside lineations are apparent these indicate an oblique-slip component (plunging approximately 60° to the west-south-west). In places faulting is associated with the local development of spaced fracture fabrics. Geophysical, geological and topographical evidence suggests that major north–south faulting also extends through areas currently obscured by ice. A major fault, downthrowing to the west, is inferred to run along the Vivaldi Glacier to the west of the Lully Foothills (Edwards, 1980*a*), since the Tertiary calc-alkaline volcanic rocks of the Colbert Mountains to the west lie at the same topographical level as the older LeMay Group rocks to the east. A similar fault may run through Quinault Pass and could be responsible for the current juxtaposition of the Lully Foothills rocks with those of the LeMay Range. The LeMay Range Fault, a major north–south-trending structure (Edwards, 1980*b*), marks the boundary of the LeMay Group with the Fossil Bluff Formation to the east, and probably represents the western margin of the George VI Sound fault system (Crabtree and others, 1985).

In addition to the north–south-trending faults, east–west-trending structures downthrowing both to the north and south were also recognized in both the eastern and western LeMay Range. Low-angle faults cutting through stacked or folded strata are present in both the eastern and western LeMay Range. In the east these are of highly variable orientation and indeterminate sense of movement, but to the west they strike north–south, and bed offsets indicate a top to the west thrust sense of movement.

(ii) *Quartz veining*. Late-stage veining is common in both the LeMay Group of the eastern LeMay Range and the adjacent Fossil Bluff Formation. One set of veins is subvertical and strikes approximately west-south-west–east-north-east, the other dips moderately to the north-east but with a high degree of scatter.

(iii) *Folding*. Grikurov (1971) interpreted the overall structure of central Alexander Island as a large, north-north-west-striking anticline with local refolding in the hinge, and Edwards (1980*a*) describes a large anticline between the Lully Foothills and the western LeMay Range (presumably the same structure) as an 'F_2' structure. The present study confirms the existence of this structure, but its relationship to other structures is equivocal. A crenulation fabric affecting the S_1 cleavage is rarely developed in some areas of the western LeMay Range and eastern Lully Foothills (i.e. in the core of the anticlinal structure). The cleavage planes strike approximately north-north-west–south-south-east and divide the rock into domains of 1 cm or less in width. Crenulation-fold axial planes are parallel to the cleavage, and their axes plunge moderately to both the north-north-west and south-south-east. Although the existence of this crenulation fabric cross-cutting the S_1 cleavage may indicate that the anticline is an F_2 structure, elsewhere the fold apparently re-orientates and therefore postdates D_2 structures.

Structural Synthesis

In developing a coherent model for the structural evolution of the LeMay Group of central Alexander Island, the following general points should be noted.

(i) The rocks of this part of the LeMay Group were deformed in a spectrum of physical conditions related to their position within the complex during deformation.

(ii) Style and intensity of deformation are strongly influenced by lithological variations within and between tectonostratigraphic units.

(iii) Given the probable long history of sedimentation and deformation in the LeMay Group, its structural development must be regarded as a continuous process, with diachronous relationships between deformational events.

(iv) Late-stage movements have juxtaposed blocks from differing structural levels, so that original relationships between units may have been modified.

The assignment of the LeMay Group to an accretionary prism environment has been made by previous authors (e.g. Edwards, 1980*a*; Burn, 1984; Storey and Garrett, 1985). Geological evidence cited by these authors for such an environment includes the situation of the group on the oceanward side of a magmatic arc, the localized occurrence of blue amphibole-bearing rocks indicating elevated pressure–temperature gradients, the polyphase nature of deformation including zones of ?tectonic mélange, and the association of cherts, pillow lavas and metasedimentary rocks. Although these geological features are all consistent with such an accretionary setting, they are not diagnostic. Whilst the sea-floor magnetic record provides unequivocal evidence that oceanic crust has been subducted beneath the Antarctic Peninsula to the west of Alexander Island from about 50 Ma ago to the present day, the pre-Cenozoic configuration is only very poorly known (Barker, 1982). The lack of a diagnostic set of geological criteria for the recognition of ancient on-land subduction complexes has hampered interpretation in other, better-known orogenic belts, and even the origin of comparatively well-documented examples, e.g. the Lower Palaeozoic Southern Uplands of Scotland and Ireland (Leggett and others, 1983) is still the subject of debate (Murphy and Hutton, 1986). Despite these limitations, the structural data for the LeMay Group described above, together with lithological and sedimentological data, can be consistently incorporated into an accretionary prism model (cf. Dickinson and Seely, 1979). Fig. 13 shows the environments of deformation envisaged for various parts of the LeMay Group of central Alexander Island.

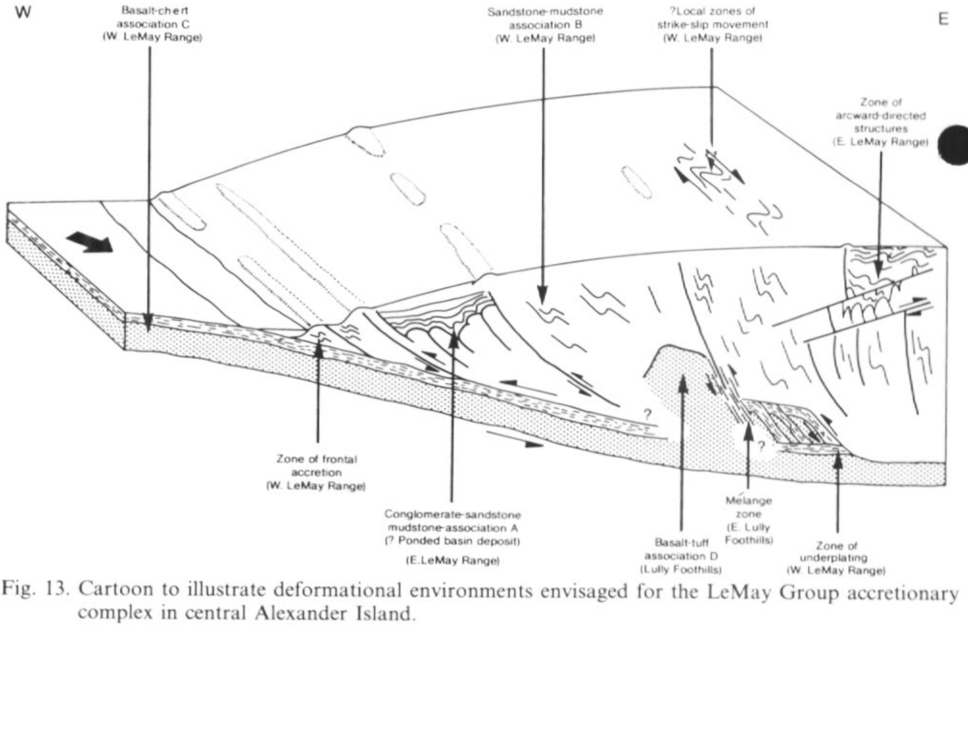

Fig. 13. Cartoon to illustrate deformational environments envisaged for the LeMay Group accretionary complex in central Alexander Island.

D_1 deformation throughout the area is interpreted as the response of a variety of rock types at different stages of lithification to a shearing couple initiated by subduction. The widespread soft-sediment stratal disruption in association A of the eastern LeMay Range represents deformation of a near-surface, poorly lithified part of the complex. The paucity of true accretion-related D_1 thrusting, together with sedimentological evidence, may indicate deposition in some form of trench-slope basin, since it is likely that such ponded deposits would have escaped much of the thrusting which affects the underlying material (Moore and Karig, 1976; Smith and others, 1979). In contrast, D_1 deformation in the western LeMay Range is dominated by westward- (oceanward-) directed thrusting at a variety of structural levels within the accretionary complex. High-level thrusting of poorly lithified sediments (e.g. in the Corelli Horn area) represents a zone of frontal accretion (Davis and others, 1983; Platt, 1986), where material accumulated at the tip of the accretionary wedge and was progressively shortened. The higher-grade, deeper-level conditions of D_1 thrusting in the cherts and basalts of association C may represent part of an uplifted underplated zone (Cowan and Silling, 1978; Silver and others, 1985). Here, material was added to the base of the wedge from the underthrusting plate at some distance from the toe of the wedge by processes such as duplex accretion (Sample and Fisher, 1986). It may be significant that occurrences of blue amphibole-bearing metabasalts were recorded from this area (Edwards, 1980*a*), since underplating mechanisms may be responsible for the 'jacking up' of buried material to higher structural levels within accretionary complexes (Platt, 1986).

The D_1 mélange zone on the eastern boundary of the Lully Foothills is interpreted as a suture between the Lully Foothills Formation, a large block of volcanic material, and other parts of the accretionary complex. The details of the sub-surface structure of this block and its margins are uncertain, but modelling of the Bouguer anomaly over this basic body suggests that, using reasonable density contrasts, it extends to a depth of at least 4 km (Garrett and Storey, 1987). The Lully Foothills are thus envisaged as an allochthonous, tectonically bounded terrane accreted to the continental margin, possibly representing a seamount or oceanic island. This contrasts with an earlier interpretation (Smellie, 1981), which envisaged the sequence as an autochthonous ponded fore-arc accumulation. Available geochemical evidence from the volcanic rocks is at present sparse and inconclusive, but the basalts appear to show affinities with ocean-floor or within-plate basalts (Burn, 1984).

Belts of arcward-directed structures, analogous to the D_2 structures identified in the eastern LeMay Range, have been recognized in other accretionary complexes. Explanations for the origin of these features, which are not predicted in the simplest models of accretionary development, are varied, and include both external factors such as continental collision (Knipe and Needham, 1986) and internal processes in the prism. These include major backthrusting due to internal shortening and thickening within the prism (Moore and Karig, 1980; Platt, 1986) and the presence of anisotropies in the subducting or accreting material; for example, base-of-slope ponded sediment accumulations and topographic highs on the underthrusting plate (Seely, 1977; Moore and Allwardt, 1980), which lead to obductive offscraping. Variations in subduction parameters, for example the rate of subduction or the angle of the descending slab, may also generate stresses which can be relieved by the formation of arcward-directed structures (e.g. Karig and others, 1980). In the LeMay Group, the origin and timing of landward-directed structures must for the present remain speculative. However, an episode of similar eastward-directed thrusting of poorly constrained age (between the mid-Cretaceous and Miocene) has been described from the Fossil Bluff Formation fore-arc basin sequence to the east (Taylor and others, 1979), although there is no evidence to suggest that the two can be correlated.

The downward-facing D_2 structures in the western LeMay Range may represent a local zone of strike-slip or oblique-slip movement within the prism and may be related to zones of steeply plunging folds identified farther to the north (Nell and Storey, in press). Although plate kinematics prior to the late Mesozoic are poorly constrained, comparison with known plate vectors up to 100 Ma ago (Barker, 1982) shows that oblique subduction was likely to have occurred along segments of the Antarctic Peninsula margin. It is possible that partitioning of strain into areas of essentially dip-slip and strike-slip components may be responsible for some of the observed lateral variations in structural style, as described from other areas of oblique convergence (e.g. Karig, 1978).

Interpretation and correlation of the late structures in the LeMay Group is complicated by their local nature. The minor, low-angle, westward-directed thrust faults probably represent the continued development of accretionary structures within the prism, but other structures may reflect different processes. The widespread north–south sets of faults common throughout Alexander Island and parts of the peninsula represent Cenozoic intra-arc extensional events related to the cessation of subduction (Garrett and Storey, 1987), although the recognition of oblique slickensides, and the strike-slip nature of deformation in the adjacent Fossil Formation (Nell and Storey, in press) may indicate the importance of oblique-slip tectonics during the later stages of fore-arc development.

Summary

The polyphase structural history of the LeMay Group of central Alexander Island can be interpreted in terms of accretion–subduction tectonics, consistent with its position on the oceanward side of the Mesozoic volcanic arc of the Antarctic Peninsula. Distinct tectonostratigraphic units can be recognized within the group, and these can be related to specific environments of deposition and deformation. Units recognized include autochthonous siliciclastic accumulations and allochthonous blocks of volcanics and associated sedimentary rocks.

The earliest deformational episode recognized in all areas led to stratal disruption of poorly lithified sediments, and is in part genetically related to a phase of thrusting in rocks at all stages of lithification. A phase of arcward-verging folds and arcward-directed thrusts deformed these earliest structures in places, and was related to either internal or external changes in the stress field of the developing complex. A local zone of downward-facing strata of equivocal origin is developed in the western LeMay Range. Later structures represent Cenozoic extensional tectonism and some show evidence of oblique-slip motion.

Acknowledgements

I wish to thank R. M. V. Summerson and N. St J. Young for their excellent field support. The manuscript benefited greatly during its preparation from discussions with colleagues at BAS. Drs S. W. Garrett, P. A. R. Nell and B. C. Storey constructively criticized an earlier draft. Dr D. T. Needham is thanked for his helpful review.

Received 16 July 1987; accepted 4 August 1987

References

Bachmann, S. B. 1982. The Coastal Belt of the Franciscan: youngest phase of northern California subduction. (*In* Leggett, J. K. *ed. Trench-forearc geology*. Special Publication of the Geological Society of London, No. 10, 401–17.)

Barker, P. F. 1982. The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest–trench interactions. *Journal of the Geological Society of London*, **139**, 787–802.

Barker, P. F. *and* Griffiths, D. H. 1977. Towards a more certain reconstruction of Gondwanaland. *Philosophical Transactions of the Royal Society of London*, Series A, **271**, 151–83.

Bell, C. M. 1973. The geology of southern Alexander Island. *British Antarctic Survey Bulletin*, No. 33–34, 1–16.

Bell, C. M. 1974. Geological observations in northern Alexander Island. *British Antarctic Survey Bulletin*, No. 39, 35–44.

Bell, C. M. 1975. Structural geology of parts of Alexander Island. *British Antarctic Survey Bulletin*, No. 41–42, 43–58.

Boyer, S. E. *and* Elliott, D. 1982. Thrust systems. *Bulletin of the American Association of Petroleum Geologists*, **66**, 1196–230.

Burn, R. W. 1984. The geology of the LeMay Group of Alexander Island. *British Antarctic Survey Scientific Reports*, No. 109, 65 pp.

Burn, R. W. *and* Thomson, M. R. A. 1981. Late Cenozoic tillites associated with intraglacial volcanic rocks, lesser Antarctica. (*In* Hambrey, M. J. *and* Harland, W. B. *eds. Earth's pre-Pleistocene glacial record.* Cambridge, Cambridge University Press, 199–203.)

Butterworth, P. J. 1985. Report on Antarctic fieldwork: sedimentology of Ablation Valley, Alexander Island. *British Antarctic Survey Bulletin*, No. 66, 73–82.

Care, B. W. 1980. The geology of Rothschild Island, north-west Alexander Island. *British Antarctic Survey Bulletin*, No. 50, 87–112.

Cowan, D. S. *and* Silling, R. M. 1978. A dynamic scaled model of accretion at trenches and its implications for the tectonic evolution of subduction complexes. *Journal of Geophysical Research*, **83**, 5389–96.

Crabtree, R. D., Storey, B. C. *and* Doake, C. S. M. 1985. The structural evolution of George VI Sound, Antarctic Peninsula. *Tectonophysics*, **114**, 431–42.

Davis, D., Suppe, J. *and* Dahlen, F. A. 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *Journal of Geophysical Research*, **88**, 1153–72.

Dickinson, W. R. *and* Seely, D. R. 1979. Structure and stratigraphy of forearc regions. *Bulletin of the American Association of Petroleum Geologists*, **63**, 2–31.

Edwards, C. W. 1980*a*. The geology of eastern and central Alexander Island. Unpublished PhD thesis, University of Birmingham, 228 pp.

Edwards, C. W. 1980*b*. New evidence of major faulting on Alexander Island. *British Antarctic Survey Bulletin*, No. 49, 15–20.

Garrett, S. W. *and* Storey, B. C. 1987. Lithospheric extension on the Antarctic Peninsula during Cenozoic subduction. (*In* Coward, M. P., Dewey, J. F. *and* Hancock, P. L. *eds. Continental extensional tectonics*. Special Publication of the Geological Society of London, No. 28, 419–31.)

Grikurov, G. E. 1971. Geologischeskoe stroenie tsentral'noy chasti Zemli Aleksandra I (The geological structure of the central part of Alexander I Land). (*In Antarktika, Mezhduvedomstvennaya komissiya po izucheniyu Antarktiki* [Antarctica, Interdepartmental commission for the study of the Antarctic]. Moskva, Izdatel'stvo Nauka, 13–42.)

Grikurov, G. E. *and* Dibner, A. F. 1968. Novye dannye o serii Triniti (C_{1-3}) v zapadnoy Antarktide. *Doklady Academii Nauk SSSR*, Geology, **179**, No. 2, 410–12. [More information on the Trinity Series (C_{1-3}) of western Antarctica. *Doklady (Proceedings) of the Academy of Sciences of the USSR*, Geological Sciences Section, **179**, 39–41.]

Grikurov, G. E., Krylov, A. Ya. *and* Silin, Yu. I. 1967. Absolyutnvy vozrast netkotorykh porod dugi Skotiya i Zemli Aleksandra I (Zapadnaya Antarktika). *Doklady Academii Nauk SSSR*, Geology, **172**, 168–71. [Absolute age of some rocks from the Scotia Arc and Alexander I Land (Western Antarctica). *Doklady (Proceedings) of the Academy of Sciences of the USSR*, Geological Sciences Section, **172**, 19–22.]

Karig, D. E. 1978. Material transport within accretionary prisms and the 'knocker' problem. *Journal of Geology*, **88**, 27–39.

Karig, D. E., Lawrence, M. B., Moore, G. F. *and* Curray, J. R. 1980. Structural framework of the forearc basin, N.W. Sumatra. *Journal of the Geological Society of London*, **137**, 77–91.

King, L. 1964. Pre-glacial geomorphology of Alexander Island. (*In* Adie, R. J. *ed. Antarctic geology*. Amsterdam, North-Holland, 53–64.)

Kleist, J. R. 1974. Deformation by soft sediment extension in the Coastal Belt, Franciscan Complex. *Geology*, **2**, 501–4.

Knipe, R. J. *and* Needham, D. T. 1986. Deformation processes in accretionary wedges – examples from the SW margin of the Southern Uplands, Scotland. (*In* Coward, M. P. *and* Ries, A. C. *eds. Collision Tectonics*. Special Publication of the Geological Society of London, **19**, 51–65.)

Leggett, J. K., McKerrow, W. S. *and* Soper, N. J. 1983. A model for the crustal evolution of southern Scotland. *Tectonics*, **2**, 187–210.

Moore, G. F. *and* Karig, D. E. 1976. Development of sedimentary basins on the lower trench slope. *Geology*, **4**, 693–7.

Moore, G. F. *and* Karig, D. E. 1980. Structural geology of Nias Island, Indonesia: implications for subduction zone tectonics. *American Journal of Science*, **280**, 193–223.

Moore, J. C. *and* Allwardt, A. 1980. Progressive deformation of a Tertiary trench slope, Kodiak Islands, Alaska. *Journal of Geophysical Research*, **85**, 4741–56.

Murphy, F. C. *and* Hutton, D. H. W. 1986. Is the Southern Uplands of Scotland really an accretionary prism? *Geology*, **14**, 354–7.

Naylor, M. A. 1982. The Casanova complex of the northern Apennines: a mélange formed on a distal passive continental margin. *Journal of Structural Geology*, **4**, 1–18.

Nell, P. A. R. *and* Storey, B. C. In press. Strike-slip tectonics within the Antarctic Peninsula forea[illegible] *Proceedings of the Fifth International Symposium on Antarctic Earth Sciences*, Cambri[illegible] Cambridge University Press.

Platt, J. P. 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Bulletin of the Geological Society of America*, **97**, 1037–53.

Sample, J. C. *and* Fisher, D. M. 1986. Duplex accretion and underplating in an ancient accretionary complex, Kodiak Islands, Alaska. *Geology*, **14**, 160–3.

Saunders, A. D., Weaver, S. D. *and* Tarney, J. 1982. The pattern of Antarctic Peninsula plutonism. (*In* Craddock, C. *ed. Antarctic Geoscience*. Madison, University of Wisconsin Press, 305–14.)

Schopf, J. M. 1973. Plant material from the Miers Bluff Formation of the South Shetland Islands. *Report of the Institute of Polar Studies. Ohio State University Research Foundation*, No. 45, 45 pp.

Seely, D. R. 1977. The significance of landward vergence and oblique structural trends on trench inner slopes. (*In* Talwani, M. *and* Pitman, W. C. *eds. Island arcs, deep sea trenches and back-arc basins; Maurice Ewing Series 1*, American Geophysical Union, Washington, 187–98.)

Silver, E. A., Ellis, M. J., Breen, N. A. *and* Shipley, T. H. 1985. Comments on the growth of accretionary wedges. *Geology*, **13**, 6–9.

Smellie, J. L. 1981. A complete arc-trench system recognized in Gondwana sequences of the Antarctic Peninsula region. *Geological Magazine*, **118**, 139–59.

Smith, G. W., Howell, D. G. *and* Ingersoll, R. V. 1979. Late Cretaceous trench-slope basins of central California. *Geology*, **7**, 303–6.

Storey, B. C. *and* Garrett, S. W. 1985. Crustal growth of the Antarctic Peninsula by accretion, magmatism and extension. *Geological Magazine*, **122**, 5–14.

Taylor, B. J., Thomson, M. R. A. *and* Willey, L. E. 1979. The geology of the Ablation Valley–Keystone Cliffs area, Alexander Island. *British Antarctic Survey Scientific Reports*, No. 82, 64 pp.

Thomson, M. R. A. *and* Burn, R. W. 1977. Angiosperm fossils from latitude 70° S. *Nature, London*, **269**, 139–41.

Thomson, M. R. A., Clarkson, P. D. *and* Pankhurst, R. J. 1983. The Antarctic Peninsula – a [illegible] Mesozoic–Cenozoic arc (Review). (*In* Oliver, R. C., James, P. R. *and* Jago, J. B. *eds. Antar[illegible] Earth Science*. Cambridge, Cambridge University Press, 289–94.)

Thomson, M. R. A. *and* Pankhurst, R. J. 1983. Age of post Gondwanian calc-alkaline volcanism in the Antarctic Peninsula region. (*In* Oliver, R. C., James, P. R. *and* Jago, J. B. *eds. Antarctic Earth Science*. Cambridge, Cambridge University Press, 328–33.)

Thomson, M. R. A. *and* Tranter, T. H. 1986. Early Jurassic fossils from central Alexander Island and their geological setting. *British Antarctic Survey Bulletin*, No. 70, 23–39.

Tranter, T. H. 1986. Reports on Antarctic fieldwork: the LeMay Group of central Alexander Island. *British Antarctic Survey Bulletin*, No. 71, 57–67.