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Geometry and kinematics of shear zones formed during continental extension in eastern Papua New Guinea

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Abstract—The D'Entrecasteaux Islands, eastern Papua New Guinea, lie in an area of continental extension that has been active since the mid-Miocene. During the last 4 Ma the metamorphic basement rocks composing most of the islands have been uplifted and tectonically exhumed from depths of approximately 35 km. Tectonic exhumation appears to have been controlled by deformation in broad (kilometre-scale) mylonitic shear zones. A progressive evolution is documented in the shear zones, characterized by: increasing localized deformation; a change from dominantly ductile to dominantly brittle processes; and decreasing metamorphic grade (i.e. retrograde metamorphism). The evolution is believed to be the result of uplift and cooling of the basement accompanying shear zone movement. The kinematic history of the shear zones is complex. A number of sinistrally offset extensional detachment zones separate a multiply deformed, high-grade metamorphic basement from a cover of largely undeformed ultramafic and mafic cover rocks. The detachment zones are connected by transverse shear zones. These transverse zones appear to act as sinistral strike-slip zones which also accommodate transfer motion between the detachment zones.

INTRODUCTION

In the last few million years, the metamorphic basement of the D'Entrecasteaux Islands in eastern Papua New Guinea has undergone a major deformation event, resulting in the formation of kilometre-scale ductile shear zones. These shear zones can be shown to have been active during continental extension. Deformation in the shear zones was accompanied by uplift and tectonic exhumation of deep crustal rocks originating from depths of approximately 35 km (i.e. $P \sim$ 7–11 kbars, Hill & Baldwin 1993). Deformation was also accompanied by widespread magmatism in the form of Pliocene and Quaternary volcanism and plutonism. The results of this deformation and uplift are mountainous islands composed of large, dome-shaped outcrops of high grade metamorphic rocks, i.e. metamorphic core complexes. The domes average about 15 km in diameter and may reach heights in excess of 2500 m above sea-level. This paper documents the deformation history and kinematics of the shear zones and discusses their role during the uplift and evolution of these metamorphic core complexes.

TECTONIC SETTING OF THE D'ENTRECASTEAUX ISLANDS

The D'Entrecasteaux Islands (Goodenough, Fergusson and Normanby islands, Fig. 1) lie within the complex tectonic boundary formed between the obliquely colliding Indo-Australian and Pacific plates (Luyendyk *et al.* 1973, Weissel *et al.* 1982, Honza *et al.* 1987). An active sea-floor spreading system in the Woodlark Basin is propagating westward into the islands (Weisell *et al.* 1982). The Woodlark Basin is floored by oceanic crust and is bounded to the north and south by ridges of sialic metamorphic rocks (Davies & Smith 1971), these are the Woodlark and Pocklington rises, respectively. Magnetic lineations on the sea floor (Weissel *et al.* 1982) indicate that spreading has occurred along an E–W axis, and a parallel linear zone of shallow seismicity indicates that the spreading centre is still active (Ripper 1982). Seismic activity, peralkaline volcanism and sea-floor morphology indicate that continental rifting associated with the Woodlark Basin sea-floor spreading system is propagating westward between Fergusson and Normanby islands (Francis *et al.* 1987, Benes 1990).

Ages of magnetic anomalies indicate that spreading in the Woodlark Basin began at approximately 5 Ma (Weissel *et al.* 1982). However, the eastern end of the Woodlark Basin is being subducted along the Solomon Trench and, as the oldest sea-floor is in the east, it is possible that any older oceanic crust may have been destroyed. Spreading rates are calculated to be 3.6 and 2.4 cm year^{-1} for the north and south flanks of the spreading system, respectively, indicating an overall spreading rate of 6 cm year^{-1} (Weissel *et al.* 1982).

In the continental crust immediately west of sea-floor spreading in the Woodlark Basin, recent extension is evidenced by the presence of E–W faults which define the Goodenough Bay and Milne Bay Grabens to the south of the D'Entrecasteaux Islands. Extensive E–W faulting is also evident on the Trobriand platform to the north of the islands. Patterns of seismic activity and earthquake focal mechanisms indicate E–W-trending normal faults are active throughout the area around the islands (Ripper 1982, Abers 1991).

The earliest evidence for continental extension in this area is the presence of mid-Miocene sediments in the Trobriand Basin. Subsequent deposition of deltaic or fluviatile conglomerates and sandstones during the Pliocene to Pleistocene (Tjhin 1976) most likely reflects the time of emergence of the D'Entrecasteaux Islands above sea-level as these are the only land masses close to the sedimentary basin.

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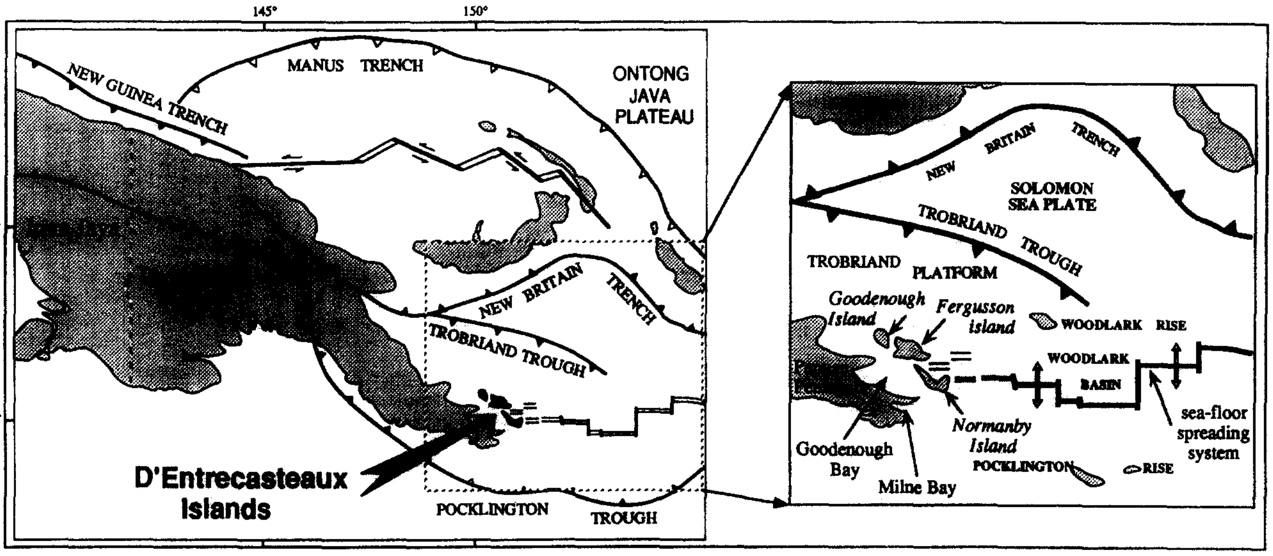

Fig. 1. Location and regional tectonic setting of the D'Entrecasteaux Islands. The islands lie at the western end of a westerly propagating sea-floor spreading system in the Woodlark Basin.

To summarize, the tectonic activity around the D'Entrecasteaux Islands is dominated by E–W-trending extensional structures including normal faulting and sea-floor spreading. Continental extension was active by the mid-Miocene.

The metamorphic basement of the islands is transected by numerous kilometre-scale ductile shear zones of amphibolite facies. The age of deformation in these shear zones is constrained by Ar–Ar and U–Pb dating to between 1 and 4 Ma (Baldwin *et al.* 1993). These shear zones, therefore, are of great interest for they document deformation that occurred at deep crustal levels during continental extension.

MACROSCOPIC STRUCTURE OF THE BASEMENT

This study focuses on the two westernmost islands: Goodenough and Fergusson islands. These consist of a basement of multiply deformed, high-grade metamorphic and plutonic rocks (Fig. 2). The metamorphic rocks include mafic and quartzofeldspathic gneisses of igneous origin and aluminous and calc-silicate gneisses that are inferred to be metasediments. The basement has suffered two phases of intrusion by granodiorite plutons. The first phase of plutonism occurred ~4 Ma (Baldwin *et al.* 1993), prior to movement on the major shear zones described below; these plutons are pervasively deformed where they intrude the shear zones. The second phase of plutonism occurred ~2 Ma, after movement on the shear zones but prior to a second phase of shearing in narrow zones. These plutons are largely undeformed except where they are cross-cut by narrow shear zones and faults. Overlying the basement are two types of cover rocks: an ultramafic cover which lies in fault contact with the basement and a sedimentary and volcanic cover of Pliocene to Quaternary age which unconformably overlies the basement and the ultramafic cover. The ultramafic rocks are probably remnants of the Papuan Ultramafic Belt, a thrust sheet of ophiolitic rocks believed to have been emplaced onto the Papuan Peninsula during the mid-Eocene or mid-Miocene (Davies & Jacques 1984, Hilyard *et al.* 1988).

The macroscopic structure of the basement is dominated by very large, kilometre-scale shear zones. These shear zones have a number of orientations and transect the basement, dividing it into a number of shear-bounded (and fault-bounded) blocks. The shear zones generally dip at moderate angles of 25–45°, but may vary in dip anywhere from vertical to horizontal (Fig. 3). The shear zones exhibit both lateral and vertical curvature and hence impart a dome-like appearance to the shear bounded blocks of basement. These shear zones commonly form dip slopes, and their geometry dominates the geomorphology of the islands.

The basement can be divided into two structural zones: a carapace and core. The carapace is the thick skin of intensely sheared rocks which overlies the core of each dome (Figs. 2 and 3). Dome-bounding faults define the upper surface of the carapace and separate the different domes. The names of the faults (see Davies 1973) have been adopted as the names for the adjacent shear zones (Fig. 2).

The carapace

The shape of each dome of metamorphic basement reflects the shape of the carapace. The carapace is defined as basement rocks which contain a pervasive mylonitic foliation and lineation on the scale of hundreds of metres; they can be readily identified on aerial photographs. The approximate thickness of the carapace varies from 300 to 1500 m (Hill 1991).

Each carapace is composed of a number of shear zones which are characterized by differently oriented lineations and foliations (Fig. 4). Where two shear zones intersect the fabrics of one shear zone curve around into the direction of the second shear zone's fabrics. As the carapace grades into the core below, shear zone fabrics

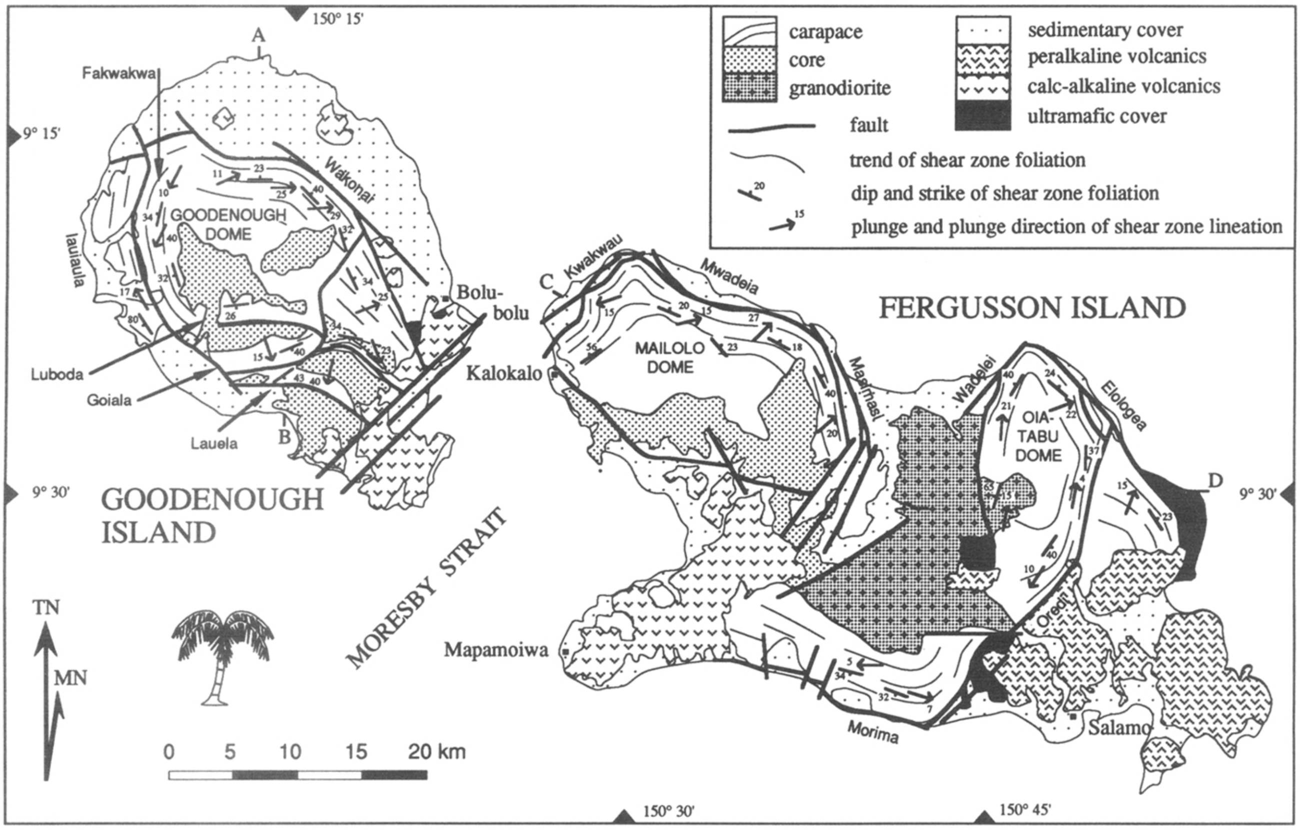

Fig. 2. Simplified geological map of Goodenough and Fergusson islands showing distribution of major lithological–structural units and representative structural data for the shear zones. The names of the composite shear zones are labelled (e.g. Fakwakwa, Wakonai, etc.). Largely undeformed ~2 Ma granodiorite plutons outcrop in many deep creek sections; however only one pluton outcrops over a sufficient area to be shown on the map.

are localized into narrow zones (a few metres thick). Deeper in the core, the effects of the shear zone deformation become progressively weaker and more localized. Shear zone fabrics overprint fabrics in the core (described below).

The dome-bounding faults

Dome-bounding faults dip at moderate to shallow angles outwards from the centres of the domes, they parallel the shear zones and mark the upper boundaries of shear zones (Figs. 2 and 3). The faults are the youngest observed structures. Previous workers have reported recent normal motion on the dome-bounding faults, and it is possible that the faults are still active (e.g. Davies & Ives 1965, Ollier & Pain 1980, Senior & Billington 1987). Dome-bounding faults separate one basement dome from another, the deformation fabrics in the basement generally change orientation abruptly across the fault. The faults also separate the basement

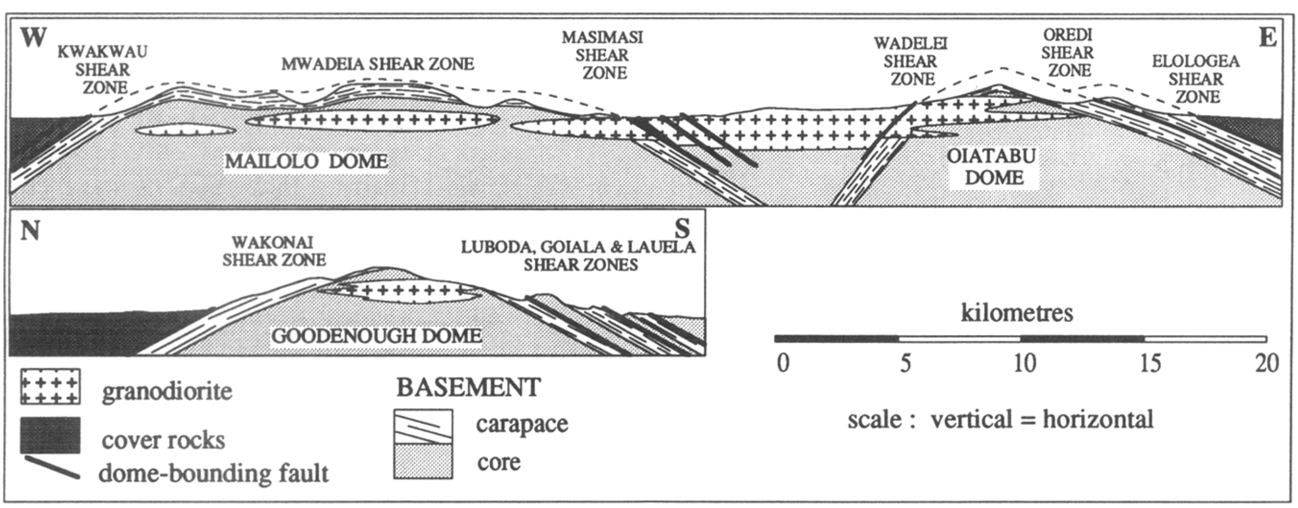

Fig. 3. E–W cross-section of Fergusson Island and N–S cross-section of Goodenough Island showing macroscopic geometry of shear zones. Location of cross-sections are shown as 'A–B' and 'C–D' on Fig. 2. The thin covering of sediments on basement and granodiorite is not shown owing to scale.

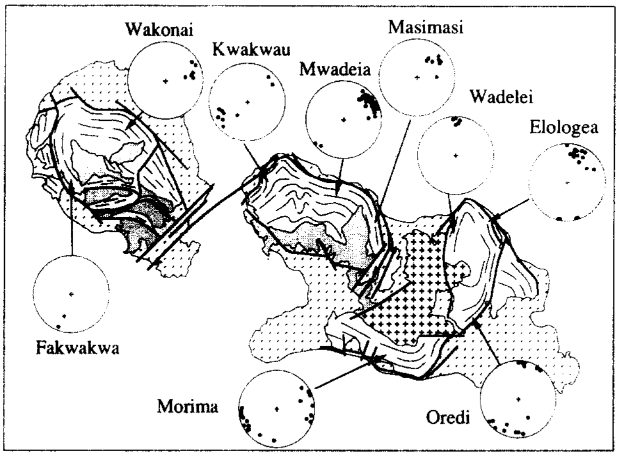

Fig. 4. Stereographic projections (equal-area) of shear zone mineral lineation (L_{3a} and L_{3b}) plotted separately for each shear zone. Locally L_{3a} and L_{3b} are parallel.

from the cover rocks (i.e. ultramafic and mafic rocks). Mapping and exploratory drilling have shown that these faults are parallel to the gneissic or mylonitic layering in the carapace shear zones both vertically and horizontally.

The core zones

Where rivers and creeks run through the carapace into the core, the very regular orientations of the shear zone fabrics give way downwards to earlier fabrics which are highly irregularly orientated. The gneisses in the core have been multiply deformed. Because the structure is very complex and outcrop is limited, little is known of the macroscopic effects of these early deformations, and they are not discussed in this paper.

The highest grades of metamorphism are preserved in the core. Peak metamorphic conditions are in the eclogite facies. Pressures up to 25 kbar have been estimated for mafic eclogities with temperatures in the range 730–900°C (Hill & Baldwin 1993, Davies & Warren 1992). However, the rocks of the core show widespread retrogression to amphibolite facies, and the carapace shear zones are pervasively retrogressed to amphibolite facies ($P \sim$ 7–11 kbars, $T \sim$ 570–730°C; Hill & Baldwin 1993). Locally, late-stage shear zones show retrogression to greenschist facies.

MESOSCOPIC STRUCTURE OF THE BASEMENT

Several generations of structures can be recognized in both the core and carapace zones of the basement. Overprinting criteria indicate that deformation in the carapace post-dates deformation in the core. Two phases of deformation can be recognized in the core (D_1 and D_2). The most recent deformation (D_3) is that which produced the fabrics and other structures of the carapace.

The structures of the core

The earliest recognizable fabric in the core is a gneissic layering (S_1 in Fig. 5a). The layered gneisses have undergone considerable recrystallization. However, elongate clumps of minerals (e.g. hornblende) and small flattened granitic veins lie parallel to the layering, and hence a metamorphic–tectonic origin is inferred for the layering. Eclogite-facies mafic dykes cross-cut the layering, indicating that this deformation event (D_1) pre-dates peak metamorphism.

Subsequent deformation (D_2) folded the compositional layering. D_2 folds are generally tight but may be isoclinal in places. Fold orientations are variable due to subsequent deformation. The axial plane foliation of D_2 folds is defined largely by retrograde plagioclase (Fig. 5b) and by alignment of granitic veins. The retrograde foliation cross-cuts the mafic eclogite dykes and therefore post-dates peak metamorphism. No deformation simultaneous to peak metamorphism was recognized.

These early structures in the core are overprinted by numerous generations of amphibolite facies shear zones. Many of the shear zones dip at low angles and, as the carapace is approached, they become more numerous until they merge with the sheared rocks in the carapace. These observations suggest that these shear zones were synchronous with deformation in the carapace.

The structures of the carapace

The carapace consists of pervasively sheared mylonites and gneisses. Tectonic layering in the sheared rocks tends to be discontinuous and often lensoidal, which may be due to isoclinal folding or extreme flattening of veins, dykes, or xenoliths (Fig. 5c). Generally the protolith of the gneisses is not recognizable due to the extreme nature of the deformation.

The shear zones which form the carapace are composite shear zones, four successive generations of structures (D_{3a}–D_{3d}) representing four separate episodes of shearing can be recognized in each of these composite shear zones (Fig. 6). The four generations of structures have identical kinematics (see below), and are regarded as an evolving sequence of structures formed during a single tectonic event. The evolution of the composite shear zones can be clearly traced from the sequence of development of these structures. The structures show progressive localization from broad ductile D_{3a} shear zones (several hundred metres thick) to the narrow D_{3d} breccia zones which form along the dome-bounding faults (generally only a few metres thick). The characteristics of each set of structures are summarized in Table 1 and will be described below using the Mwadeia shear zone on Fergusson Island as an example.

The Mwadeia shear zone

Structural notation used in this section is summarized in Table 2. The Mailolo Dome is bounded on three sides

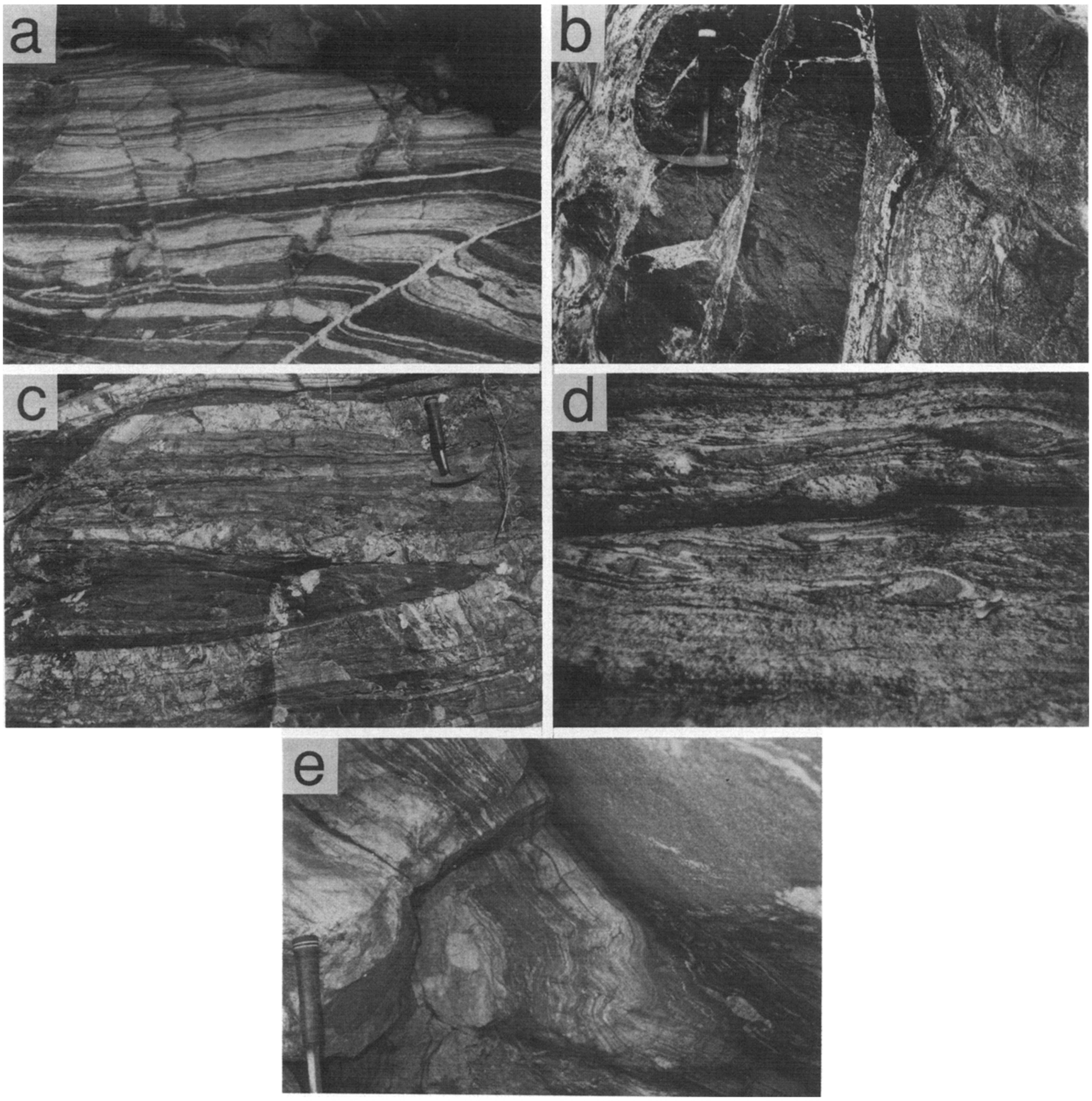

Fig. 5. (a) Layered core gneiss (gneissic layering = S_1) showing alternating mafic and felsic layers, Galuwata River, central Goodenough Island. (b) Partially retrogressed eclogite (dark layers) in layered gneiss. S_2 foliation (plagioclase) cross-cuts eclogite at high angle, Galuwata River, central Goodenough Island. (c) Isoclinically folded mafic layer in layered gneiss form the carapace, Awuetaua River, northeast Fergusson Island. (d) Rootless, isoclinical D_{3a} folds in the Mwadeia shear zone, northwest Fergusson Island. (e) Narrow D_{3b} shear zone above F_{3b} fold in layered gneiss (S_{3a}); weak development of axial plane foliation (S^{s}_{3b}), Wakonai shear zone, Goodenough Island.

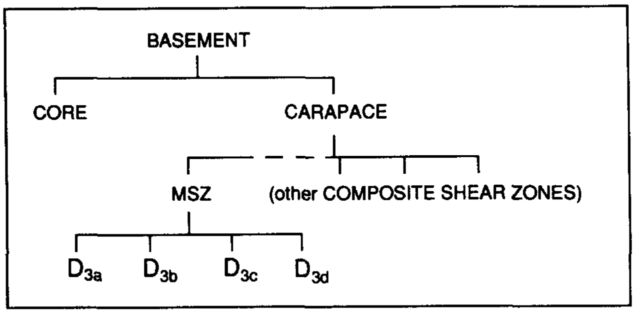

Fig. 6. Structural components of the basement (MSZ = Mwadeia shear zone). Each composite shear zone contains structures from the D_{3a} to D_{3d} episodes of shearing.

by composite shear zones: the Mwadeia shear zone (MSZ) forms the northern section of the carapace while the Masimasi and Kwakwau shear zones form the eastern and western sections, respectively. The core is exposed on the south side of the dome (Figs. 2 and 7). The major structures of the Mailolo dome are illustrated in a simplified N–S section through the dome (Fig. 8) and are as follows.

Much of the basement in the southern half of the Mailolo Dome consists of early (i.e. ~4 Ma) granodiorite. The granodiorite is undeformed in the core except in localized D_{3a} shear zones. In the carapace it is pervasively deformed, indicating that this phase of granodiorite intruded prior to or during early stages of deformation in the carapace.

Around the margins of the dome, the MSZ dips 20–30°NNE. Near the top of the dome the shear zone flattens out and becomes slightly warped (Figs. 7 and 8). A pervasive mylonitic foliation (S_{3a}) is developed throughout the MSZ. The D_{3a} shear zone was locally subjected to high temperatures (570–730°C) during and after formation due to the intrusion of grandiorite plutons (Hill & Baldwin 1993). As a result, many of the mylonites have been recrystallized to coarse-grained gneisses. However, in localized areas, a fine-grained mylonitic fabric is preserved. The S_{3a} foliation is axial planar to isoclinal, rootless intrafolial folds (Fig. 5d). All previous fabrics are transposed parallel to the shear zone foliation. An ENE-trending mineral lineation is also developed throughout the shear zone, resulting in a strong *L–S* tectonite fabric in the shear zone rocks. All fold hinges are parallel to this mineral lineation.

Following the development of the broad shear zones (D_{3a}), deformation became progressively localized (D_{3b}–D_{3d}), the youngest structure (i.e. D_{3d}) being the Mwadeia Fault. This sequence of shear zone development is paralleled by an increasing degree of retrograde metamorphism; i. e. there is a decrease in metamorphic grade from upper amphibolite facies in the D_{3a} MSZ to greenschist facies around the Mwadeia Fault (D_{3d}).

The D_{3b} shear zones are distributed throughout the carapace; they range from a few centimetres to 1 m thick and may extend laterally (i.e. parallel to the foliation) for several hundred metres (Fig. 5e). These shear zones are believed to be responsible for the step-like 'facets' on the shear zone dip-slopes described by previous authors (e.g. Ollier & Pain 1980, Senior & Billington 1987). D_{3b} shear zones have an undulatory form but are generally parallel or sub-parallel to the D_{3a} shear zone fabric (Fig. 9). The mineral lineation in the D_{3b} shear zones trends ENE, parallel to that in the D_{3a} shear zones. The D_{3b} shear zones are associated with asymmetric folds of the earlier S_{3a} foliation (Fig. 5e). The axial plane foliation of the folds lies at an angle to the shear zone foliation (S^{s}_{3b} and S^{c}_{3b}, respectively, Table 2). This angle decreases where the folds are very tight or isoclinal and the axial plane fabric is more intense.

The second set of narrow shear zones (D_{3c}) are also only a few centimetres thick, however they cross-cut the D_{3a} shear zone fabric at angles of approximately 45° or

Table 1. Characteristics of different generations of shear zones in the carapace, i.e. D_3 structures

	Description	Extent of fabric development	Relative orientation of shear zone
D_{3a}	Pervasive development of shear zone fabric over a thickness of several hundred metres	The carapace is defined as areas in which this shear zone fabric is pervasively developed	The fabric is parallel to the carapace boundaries
	Fabrics are amphibolite facies	The fabric is also locally developed in narrow shear zones in the core (i.e. generally <1 m thick)	
D_{3b}	Narrow shear zones, only a few tens of centimetres thick, but may extend over several hundred metres in length	These narrow shear zones are found in abundance within the boundaries of the carapace It is possible that some of the shear zones in the core are of the same generation of structures	The shear zones undulate but their enveloping surface is broadly parallel to the carapace boundaries and the D_{3a} fabric; locally they may truncate the D_{3a} fabric at low angles
D_{3c}	Narrow shear zones, generally only a few centimetres thick and less than 1 m long	These narrow shear zones are found in abundance within the boundaries of the carapace	These shear zones are not parallel to the carapace boundaries and they truncate the D_{3a} and D_{3b} fabrics at moderate angles (approximately 45°).
	They may occur as conjugate pairs	It is possible that some of the shear zones in the core are of the same generation of structures	
D_{3d}	Zones of schistosity, crenulation and brecciation	These zones are restricted to forming along the dome-bounding faults; i.e. along the upper surface of the carapace	These zones form parallel to the dome-bounding faults which are parallel to the upper boundary of the carapace
	Fabrics are greenschist facies		

Table 2. Summary of fabric notation used in text. The superscript 's' indicates a fold axial plane fabric, and 'c' indicates a shear zone fabric (this terminology is adapted from that used to distinguish fabrics in *S–C* mylonites)

Deformation event	Fabric	Fabric type
D_1 (core)	S_1	Gneissic fabric parallel to tectonic layering (pre-eclogite)
D_2 (core)	S_2	Retrograde foliation (post-eclogite)
D_{3a} (carapace)	S_{3a}	Pervasive amphibolite-facies shear zone fabric in carapace
D_{3b} (carapace)	S^c_{3b}	Localized amphibolite-facies shear zone fabric in carapace
	S^s_{3b}	Localized amphibolite-facies foliation forming axial planar to folds associated with D_{3b} shear zones

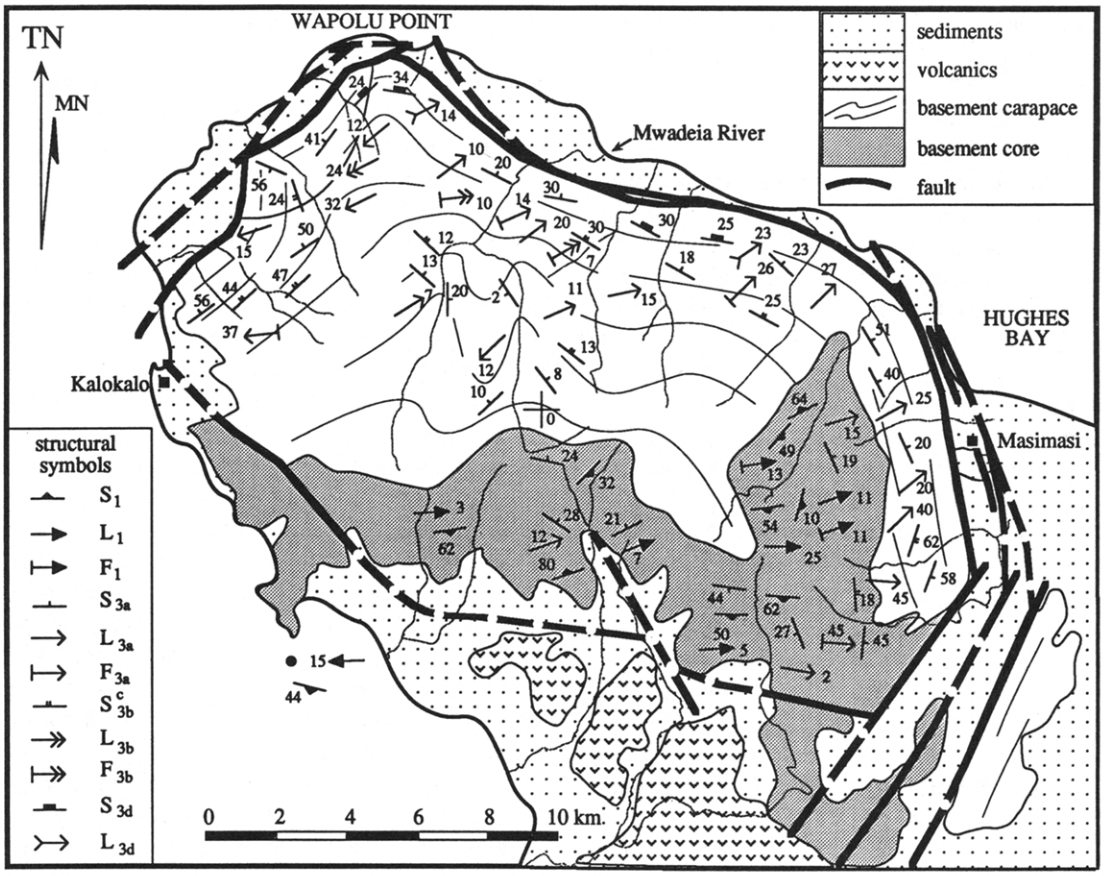

Fig. 7. Detailed structure of the Mailolo Dome, northwest Fergusson Island, showing orientation of major fabric elements in basement gneisses. '*S*' fabric elements are gneissic foliation or schistosity. '*L*' fabric elements are mineral lineations. Thin lines in carapace show trend of shear zone foliation (S_{3a}). Dotted lines are rivers and creeks.

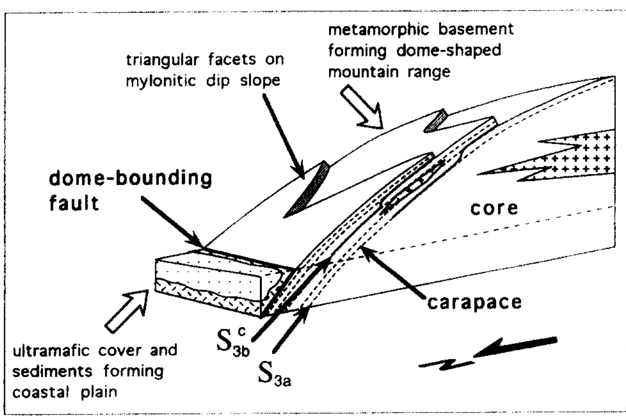

Fig. 8. Schematic N–S section across the Mailolo Dome showing major structural units: (1) complexly deformed core; (2) mylonitic carapace (S_{3a}, ~400 m wide), overprinted locally by sub-parallel narrow shear zones (S^c_{3b}); (3) dome-bounding fault developed parallel to shear zone; and (4) basement overlain by cover of ultramafic rocks, volcanics and sediments.

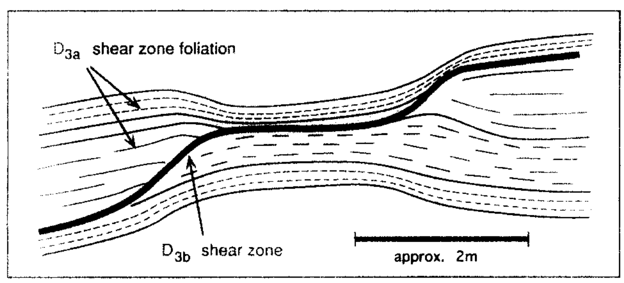

Fig. 9. Sketch of undulating D_{3b} shear zone cross-cutting earlier S_{3a} foliation. The D_{3b} shear zone is broadly parallel to the earlier fabric but locally may cut across it at moderate angles.

greater and are only 1–2 m in length (parallel to the foliation). In vertical sections these shear zones show a normal sense of displacement and commonly occur in conjugate pairs, indicating that during D_{3c} extension occurred sub-parallel to the earlier D_{3a} fabric.

The third set of narrow shear zones (and breccias) are those associated with the dome-bounding fault (D_{3d}), in this case the Mwadeia fault. These shear zones are the most recent structures and are confined to the upper surface of the carapace. The zones are generally only a few metres thick, but may be broader (100–200 m) where two of the dome-bounding faults intersect. The fault zone typically consists of fragments of quartzo-feldspathic gneiss in a matrix of biotite–actinolite or chlorite–actinolite schist. The fault zone may also contain talc schist or serpentinite from the ultramafic cover rocks. The schists are strongly foliated and lineated, and display localized folding and crenulation. Mineral lineations in the schist and rare slickenside lineations trend ENE, parallel to the mineral lineation in the MSZ.

Evolution of the shear zones

The sequence of structures outlined for the Mwadeia shear zone can be found in all the composite shear zones that make up the carapace of the domes on Goodenough and Fergusson islands. During the evolution of each composite shear zone there were four distinct episodes of shearing (D_{3a}–D_{3d}) which became progressively more localized with time. Evolution of the shear zones was characterized by a change from dominantly ductile (i.e. mylonitization) to dominantly brittle processes (i.e. brecciation) and decreasing metamorphic grade. During the evolution of the shear zones the carapace and core of the basement were being uplifted and exhumed (Hill & Baldwin 1993).

KINEMATICS OF THE SHEAR ZONES

Sense of shear in the D_{3a} shear zones

There is a well-developed mineral lineation (L_{3a}) in the shear zones defined by stretched or aligned minerals (e.g. quartz or hornblende). Pre-existing linear structures in the shear zones (e.g. fold axes) are oriented (or have been reoriented) parallel to L_{3a}. L_{3a} is parallel to the direction of maximum extension as indicated by: (1) boudinage and necking of competent layers parallel to L_{3a}; (2) quartz-filled tension fractures perpendicular to L_{3a}; (3) deformed granitic veins in migmatites stretched parallel to L_{3a}; (4) boudinage of garnet and muscovite grains parallel to L_{3a}; and (5) pressure shadows around garnet porphyroblasts and feldspar porphyroclasts parallel to L_{3a}. The mineral lineation has consistent orientation within each shear zone (Fig. 4) and, as it is parallel to the direction of maximum extension in each shear zone, the lineation can be used to indicate the line of tectonic transport. The sense of asymmetry can be used to determine the sense of movement in the shear zone (e.g. Lister & Snoke 1984, Passchier & Simpson 1986).

In these mylonites asymmetric pressure shadows on garnet and feldspar porphyroclasts and *S–C* fabrics, asymmetric microshears and mica fish in micaceous mylonites indicate that deformation was non-coaxial. Mesoscopic and miscroscopic structures indicate that NW- or WNW-trending shear zones with oblique stretching lineations (i.e. Galuwata, Mwadeia and Elologea) had a normal component of movement (Hill 1991). Sinistral asymmetry is indicated by microstructures in the approximately N-trending Oredi shear zone and also in a sample from the N-trending Fakwakwa shear zone. Sinistral sense of shear is indicated by several samples from the W-trending Morima shear zone.

Sense of shear in post D_{3a} shear zones and faults

In the D_{3b} and D_{3d} shear zones the shear zone lineations are defined by the alignment of elongate minerals (e.g. actinolite, clinozoisite) and stretched grains (e.g. quartz and pseudomorphic replacements of earlier minerals). Locally, the mineral lineation in the D_{3b} and D_{3d} shear zones is parallel to L_{3a}. Displacement of layering, foliation and dykes across D_{3b} shear zones and late minor faults (D_{3d}) is normal, i.e. consistent with the sense of shear in the local D_{3a} mylonites. These two factors indicate that the direction of tectonic transport in the composite shear zones has remained constant throughout the evolution of the carapace.

The D_{3c} shear zones are not parallel to the D_{3a}, D_{3b} or D_{3d} shear zones and hence their sense of shear is not comparable. However, the presence of conjugate pairs of normal shear zones in the Mwadeia shear zone, as discussed above, and in the Wakonai shear zone indicates extension parallel to the mylonitic foliation, which is consistent with the normal sense of shear reported for the D_{3a} episode of deformation in these shear zones.

TYPES OF COMPOSITE SHEAR ZONES

The orientation of the mineral lineation, while remarkably consistent within each composite shear zone, varies considerably between the composite shear zones (Fig. 4). There is no obvious pattern to the lineations. However, the shear zones can be divided into three groups based on similarities between shear zone and fabric orientations and the nature of the rocks in the hangingwall of the shear zone. The three groups are termed the detachment, transverse and antithetic shear zones. The differences between the groups of shear zones is described below.

Detachment shear zones (and their overlying dome-bounding faults) form the carapace on the northeastern sides of the domes (i.e. Wakonai, Elologea, Masimasi and Mwadeia shear zones, Fig. 2). These shear zones dip towards the north or northeast, and stretching lineations plunge shallowly northeast or east, strongly oblique or perpendicular to the strike of the shear zones. These faults are overlain only by ultramafic (or associated mafic) cover rocks. No metamorphic basement has been reported north of (i.e. above) these shear zones and faults. Therefore, they form the main detachment surface between the largely undeformed ultramafic cover and the multiply deformed metamorphic basement.

Transverse shear zones (and their overlying dome-bounding faults) cut across the detachment shear zones and separate the domes from each other. They trend approximately N–S or NNW–SSE (i.e. Iauiaula, Fakwakwa, Kwakwau, Wadelei and Oredi shear zones, Fig. 2). Lineations in these shear zones trend parallel or sub-parallel to the strike of the shear zones. The composition of the hangingwall may change along the length of these shear zones. For example, ultramafic cover rocks overlie the Oredi shear zone along the eastern side of the Oiatabu Dome (Fig. 2), but basement rocks overlie the Oredi shear zone in the north.

Antithetic shear zones (i.e. Luboda, Goiala and Lauela shear zones) lie on the south side of the Goodenough Dome and dip in the opposite direction to the detachment shear zone (i.e. the Wakonai shear zone). The shear zones are stacked parallel to each other and all contain metamorphic basement in the hangingwalls. Minor amounts of sheared ultramafic cover rock have been reported from the fault zones which bound the upper surface of antithetic shear zones (Davies & Ives 1965).

The Morima shear zone on southern Fergusson Island does not fit into any of these groups. The Morima shear zone is orientated in approximately the same direction as the detachment shear zones but dips in the opposite direction (southwards) and its lineation is sub-parallel to the strike of the shear zone, unlike the detachment or antithetic shear zones where the lineation is strongly oblique to the shear zone. Small amounts of ultramafic cover rock can be found directly above the dome-bounding fault, but the main part of the hangingwall is submerged and hence the composition of the hanging-wall is largely unknown.

DISCUSSION

Current models for dome formation

There are two models for the formation of the D'Entrecasteaux domes. The first model requires that the shear-bounded domes formed as a result of broad dome-and-basin style folding of a pre-existing sheet of foliated rocks. Davies & Warren (1988) suggest that the foliated rocks were formed as a result of thrusting. Alternatively, Masson (1984) suggests that the foliated rocks formed as an extensional detachment surface, comparable to that in the North American metamorphic core complexes. The second model requires that the shear-bounded domes formed as a result of radial shearing outwards due to a central uplifting force. In this case shearing, formation of the domes, and exhumation of the metamorphic basement occur simultaneously. This model was first proposed by Ollier & Pain (1980) who suggested that the domes formed by the forceful emplacement of granitic diapirs.

The first model implies that the carapace formed by unidirectional motion. This unidirectional motion should be reflected in a consistent pattern of stretching lineations and kinematic indicators in the carapace. Consistently orientated lineations have been reported from other areas of extensional deformation; for example, in core complexes in the western United States of America (e.g. Davis *et al.* 1986, Reynolds & Lister 1990) and in the Cyclades, Greece (Lister *et al.* 1984). Models proposed to explain this phenomenon involve broad warping of a unidirectional shear zone (e.g. Spencer 1984). These models were supported by early studies of kinematic indicators in the shear zones which found that the sense of shear was generally consistent throughout the complexes. Alternatively, if the domes formed as a result of radial shear zone movement this should also be reflected in the pattern of stretching lineations.

It is hard to rationalize the pattern of stretching lineations on the D'Entrecasteaux domes in terms of either of these models. In many cases lineations change trend abruptly by up to 90° (e.g. around the Morima–Oredi and the Elologea–Wadelei intersections). This pattern is not consistent with the broad warping of a unidirectional shear zone as suggested by previous workers but is consistent with tight folds with steeply dipping fold axes. There is, however, no evidence of the latter deformation in the mesoscopic structure of the basement, and it is therefore considered highly unlikely. Many of the shear zones have lineations which are parallel to the strike of the shear zone and hence the lineation pattern cannot be considered as radial.

Further problems are encountered with the above models for the D'Entrecasteaux Islands when the nature of the cover rocks is considered. For both the radial model and the folded shear zone model the carapace of the domes should form a single detachment surface between the metamorphic basement and the ultramafic cover, and therefore only ultramafic cover rocks should occur in the hangingwalls of the carapace shear zones. However, as both ultramafic cover rocks and basement rocks are found in the hangingwalls of some of the carapace shear zones it is clear that not all the shear zones are detachments. Only those defined here as detachment shear zones contain just ultramafic cover rocks in their hangingwalls.

The role of the detachment zones

The northeasterly-dipping detachment shear zones all indicate a normal or oblique-normal sense of shear. These shear zones form the boundary between the complexly deformed, high grade metamorphic rocks of the basement and the relatively undeformed mafic and ultramafic rocks of the cover. These cover rocks show no evidence of having suffered the complex metamorphic and structural history of the basement rocks. The juxtaposition of two such distinct units implies that significant displacement has taken place along this boundary. Therefore these shear zones and faults are considered to represent a major extensional detachment surface. It is suggested here that normal movement along this detachment surface may provide a mechanism for the uplift and tectonic exhumation of the high-grade metamorphic basement, in a manner similar to that suggested by Davis *et al.* (1986) for detachment surfaces in the North American metamorphic core complexes. The detachment shear zones are progressively offset from each other in a sinistral direction at the transverse shear zones.

The role of the transverse zones

There are two mechanisms which can result in the observed shear zone–fault geometry: (1) the transverse zones act solely as transfer zones which allow simultaneous movement on the transverse and extensional parts of the shear zones; or (2) the transverse zones are zones of strike-slip movement which have resulted in the *subsequent* sinistral displacement of sections of the detachment zone (Fig. 10).

Assuming that movement on the transverse shear zones and faults is purely the result of transfer motion between the offset sections of the detachment zone then the following points must hold: (1) the orientation of the stretching lineation in the transverse and extensional zones must be parallel; (2) both the transfer zones and the detachment zones both form the boundary between the basement and cover; (3) the transfer zones must show a dextral sense of shear to accommodate the sinistral offset; and (4) the transverse zones and detachment zones must have operated simultaneously.

The transverse shear zones do not fit a model of solely transform motion as evidenced by the following points: (1) the stretching lineations in the transverse and extensional zones are not parallel; (2) the transfer zones also operate where there is basement both above and below the zones; and (3) a number of the kinematic indicators in the transverse zones indicate sinistral motion has taken place on these shear zones.

Previous workers in the D'Entrecasteaux Islands (e.g. Davies & Ives 1965) have suggested that the domes and their bounding faults have been offset by subsequent strike-slip motion on the transverse zones. However, the shear zones are structurally continuous and as the various episodes of deformation in both the transverse and detachment shear zones formed at the same depth (as reflected by comparable metamorphic grades for same generations of structures) at the same time (from cooling history documented using Ar–Ar thermochronology, Baldwin *et al.* 1993). It can be inferred therefore that both the transverse and detachment zones were operating simultaneously at the same structural level.

New model for dome formation

A new model of dome formation is required to explain the roles of the different types of shear zones of which the domes are composed. It is proposed that the transverse shear zones are sinistral shear zones that offset the detachment zones and the domes in a sinistral direction. However, as the transverse zones were operative at the same time as the detachment zones the movement on them is complicated. The parts of the transverse shear zone which separate cover from more cover or basement from more basement will show a sinistral sense of shear. However, the part of the shear zone that separates basement from cover will also have to accommodate the relative motion between the two offset sections of the detachment zone (Fig. 11), in a similar way that transform faults allow offsets along mid-ocean ridges. The direction of motion on the 'transfer' region of the transverse zones will be dependent on the relative rates of horizontal spreading and strike-slip motion between the shear/fault bounded blocks. The orientation of the

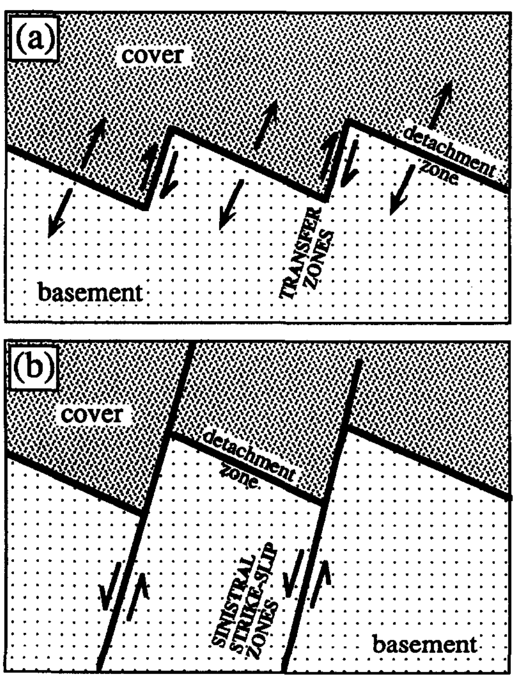

Fig. 10. Two mechanisms which can result in the observed shear zone–fault geometry: (a) transfer zones between the offset section of the detachment zone allow simultaneous movement on the transverse and extensional parts of the shear zone; (b) transverse strike-slip zones result in sinistral displacement of sections of the detachment between cover and basement.

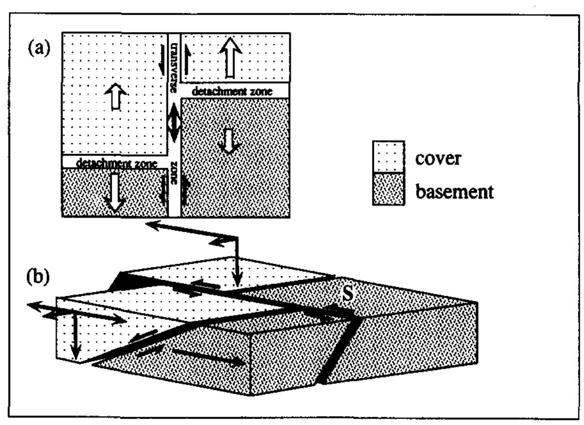

Fig. 11. Simple map (a) and block diagram (b) demonstrating possible relative motions between the structural blocks during simultaneous extensional movement on normal faults and sinistral strike-slip motion on transverse faults. Motion on the fault between the two normal faults will be a combination of the motion as a result of horizontal extension and motion as a result of strike-slip movement ('S' in b indicates stationary block).

stretching lineation and the sense of shear parallel to the lineation is a reflection of these relative motions.

The movement picture on Goodenough Island is complicated by the Goiala, Luboda and Lauela shear zones. These shear zones do not separate cover and basement; therefore they cannot have formed by folding of the Wakonai shear zone, a major detachment surface separating basement and cover, over the back of the Goodenough Dome. The orientation of the Lauela, Luboda and Goiala shear zones and their stretching lineations are consistent with an antithetic motion to the Wakonai shear zone.

The Morima shear zone on Fergusson Island is enigmatic. It shows a sinistral sense of motion and appears to be connected almost at right angles to the sinistral Oredi shear zone. The senses of shear in the intersecting Oredi and Morima shear zones are approximately orthogonal to each other. It is difficult to rationalize such a movement picture if the shear zones were operating at the same time. Thermochronology (Baldwin *et al.* 1993) indicates that the Morima shear zone has undergone a different cooling history to the other shear zones. It is possible that the kinematic indicators in the Morima shear zone may record an earlier phase of shearing.

SUMMARY

Seismic activity indicates that the D'Entrecasteaux Islands lie in an area of currently active continental extension, and sedimentary records in the adjacent Trobriand Basin suggest that continental extension has been active since the mid-Miocene. Geobarometric, geothermometric and geochronological data indicate that the exhumation of at least 35 km of metamorphic basement (during this extensional tectonic regime) occurred during the last 4 Ma; and the islands are believed to have first emerged above sea-level about the time of the Pliocene–Pleistocene boundary (approximately 2 Ma ago). The metamorphic basement has subsequently been uplifted in excess of 2500 m above sea-level. It is proposed that deformation in the shear zones accommodated horizontal crustal extension and resulted in uplift and tectonic exhumation of these deep crustal rocks.

The evolution of the shear zones can be divided up into four stages, D_{3a} to D_{3b}. The evolution is characterized by progressive localization of deformation; a change from dominantly ductile to dominantly brittle processes; and progressive retrograde metamorphism. This evolution is believed to be the result of uplift and cooling of the basement accompanying shear zone movement.

The pattern of shear zone stretching lineations around the domes and the composition of the hangingwall rocks above the shear zone bounding faults are inconsistent with previously proposed models of: (a) broad folding or warping of a sheet of foliated or unidirectionally sheared rocks; or (b) radial shearing as a result of a central uplifting force (e.g. granitic diapirs).

The shear zones which bound the northeastern sides of the domes form a major detachment surface between a complexly deformed metamorphic basement and relatively undeformed ultramafic–mafic cover. Asymmetric microstructures in mylonites and fault displacements indicate that movement on the detachment was extensional and accommodated uplift of the basement.

The detachment surface occurs as a number of shear zones which are offset from each other in a sinistral direction and connected by transverse shear zones. Evidence from the metamorphic grade of the mylonitic foliation, structural continuity of the shear zones and cooling history of the shear zones strongly suggest that the extensional detachment and the transverse shear zones were operating at the same time. Kinematic indicators in the transverse shear zones are consistent with a sinistral sense of shear along at least some parts of these shear zones. The transverse zones probably acted as sinistral strike-slip zones which also accommodate relative motion between the active extensional shear zones.

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