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Structural analysis of basement tectonites from the Aegean metamorphic core complex of Ios, Cyclades, Greece

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Abstract—The island of Ios in the Cyclades, Aegean Sea, Greece, exposes high pressure metamorphic rocks that were subjected to Miocene continental extension subsequent to the Alpine collisional orogeny. The pre-Alpine history of the lower-plate of this Aegean metamorphic core complex involves intrusion of granitoids into metasediments which subsequently underwent Hercynian amphibolite facies metamorphism. During the Alpine orogeny (D_2), these rocks were overthrust by the Cyclades blueschist nappe. Later, the lower plate was tectonically exhumed during Oligo–Miocene continental extension and associated plutonism. Final exhumation occurred as a result of the operation of a south-directed, crustal-scale shear zone and low-angle normal faults. This study shows that the Ios core complex reflects an intrinsic relationship between early thrusting and later extensional tectonism. Basement rocks have been exhumed from beneath the nappes that originally overrode them. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Lister *et al.* (1984) proposed that metamorphic and igneous rocks exposed on Ios and Naxos (Fig. 1) were juxtaposed beneath an upper-plate of non-metamorphic rocks by continental extension processes. The extension processes were suggested to have begun operation sometime during the Oligo–Miocene (25–16 Ma). Their hypothesis was based on the following observations: (1) relatively young mylonites were formed in crustal scale ductile shear zones; (2) stretching lineations were warped over elongate structural domes; (3) igneous activity coincided with uplift; (4) ductile deformation continued as temperature decreased; and (5) final juxtaposition of unmetamorphosed sediments against igneous and high grade metamorphic rocks had been accomplished by low-angle normal faulting. In this scenario, mid-to-lower crustal rocks were envisaged to have been dragged to the surface through the operation of a major top-to-the south crustal shear zone (exposed on Ios as the 'South Cyclades' shear zone) to form the Aegean metamorphic core complexes (Banga 1983, Lister *et al.* 1984). Subsequent work in the region has shown, however, that extrapolation of the Miocene kinematic data from Ios (top-to-the south) to the northern Cycladic region was erroneous. While similar deformation processes were active in the northern Cyclades, in complementary ductile shear zones the shear sense was top-to-the north or northeast (Urai *et al.* 1990, Buick 1991, Lee & Lister 1992, Gautier *et al.* 1993).

In this paper we analyse the structural geology of the lower-plate basement gneiss dome of Ios, Cyclades, Greece. Access to relatively deep structural levels of this Aegean metamorphic core complex is provided by virtue of the fact that erosion has cut down to (and occasionally through) the carapace ductile shear zone of the lower-plate.

REGIONAL SETTING

The island of Ios forms part of the Attic–Cycladic Massif (Fig. 1). Within this metamorphic belt two major tectono–metamorphic units have been recognised: a pre-Alpine basement comprising para- and ortho-gneisses (Ios, Sikinos and possibly Naxos, Andriessen *et al.* 1987) and an overlying marbleschist unit comprising metamorphosed Mesozoic carbonate, pelitic, ophiolitic and volcanic rocks (Jansen & Schuiling 1976, Dürr *et al.* 1978). During the Eocene (~50 Ma) Alpine collision of the African and European plates, the overlying metasedimentary unit was thrust over the pre-Alpine basement (Dürr *et al.* 1978, Henjes-Kunst & Kreuzer 1982, Van der Maar & Jansen 1983).

Hercynian ages (295–305 Ma) and relict amphibolite facies mineral assemblages from the Ios basement suggest an M_0 amphibolite facies metamorphism prior to the Eocene collision (Henjes-Kunst & Kreuzer 1982). Pre-Hercynian ages (500 Ma) from granitic bodies within the basement complex are interpreted as the time of intrusion of the ortho-gneiss protolith (Henjes-Kunst & Kreuzer 1982, Andriessen *et al.* 1987). Two subsequent regional Alpine metamorphic events have affected both the basement and overlying Mesozoic marbles and schists: M_1 Eocene (~50 Ma) high pressure/medium temperature eclogite/blueschist facies metamorphism (in response to the Alpine collision), and M_2 Oligo–Miocene (25–16 Ma) Barrovian-type greenschist facies overprinting (Jansen & Schuiling 1976, Altherr *et al.* 1982, Henjes-Kunst & Kreuzer 1982, Andriessen *et al.* 1987). More recent work suggests that M_2 on Naxos occurred approximately 15–16 Ma (Wijbrans & McDougall 1986, Wijbrans & McDougall 1988). Late Miocene granitoids (22–10 Ma) produced low pressure/high temperature M_3 contact metamorphism (Altherr *et al.* 1982, Wijbrans & McDougall 1986) at the same time as calc-alkaline volcanism

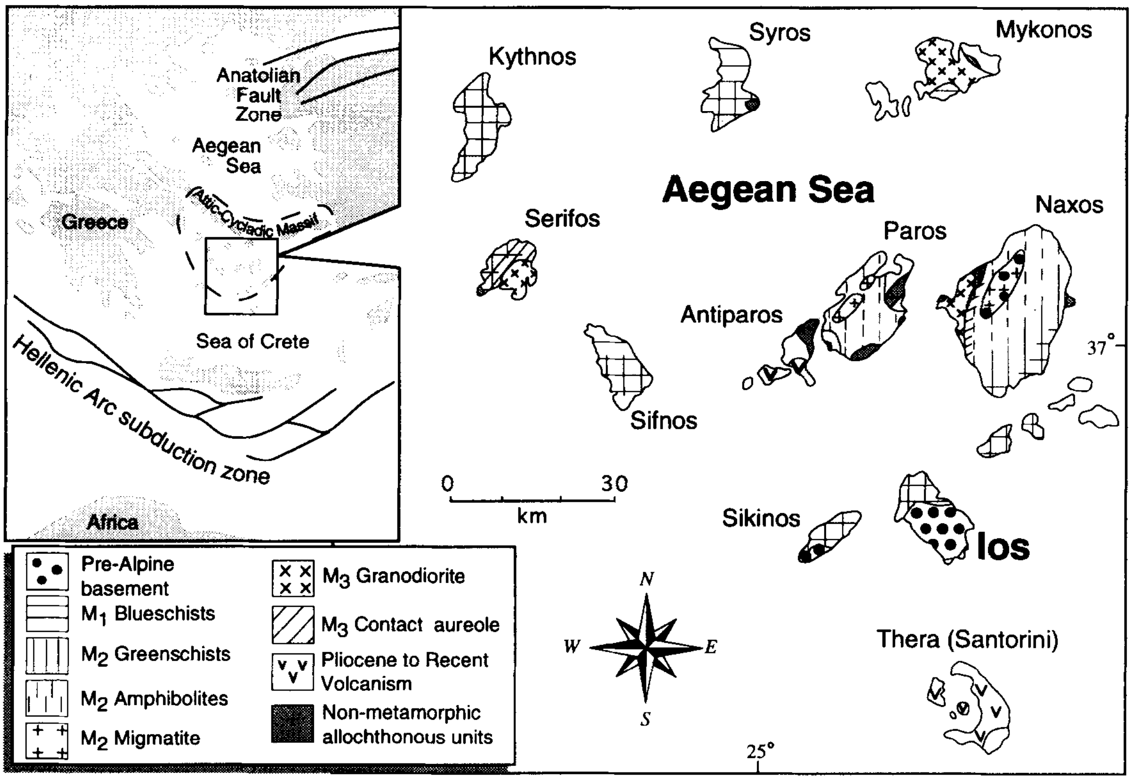

Fig. 1. Simplified geological map of metamorphic, igneous and non-metamorphic rocks exposed in the Attic–Cycladic metamorphic belt, Aegean Sea, Greece (after Altherr *et al.* 1982 and Van der Maar & Jansen 1983).

(22–13 Ma) was taking place (Borsi *et al.* 1972, Fytikas *et al.* 1976).

The Aegean is floored by attenuated continental crust (approximately 20 km thick in the Sea of Crete, Makris 1978), and tomographic imaging across the seismically active Hellenic Arc subduction zone shows a north dipping African lithospheric slab beneath the Aegean Sea (Meulenkamp *et al.* 1988). It is estimated that the slab is up to 600 km in length and that subduction began at least at 26–40 Ma (*op. cit.*). Continental extension in the Aegean region is suggested to have accompanied subduction of the African lithosphere, and normal faulting and the formation of sedimentary basins in the Sea of Crete indicates that the extension initiated at least 12–13 Ma (Le Pichon & Angelier 1979, Le Pichon & Angelier 1981, Angelier *et al.* 1982). Lister *et al.* (1984) estimated that extension began at the time of the M_2 metamorphism on Naxos (i.e. in the period 16–25 Ma). Normal faulting and syn-deformational deposition of Mio-Pliocene sediments in half grabens on Paros and Naxos suggests that regional extension probably did initiate as far back as 25 Ma (Gautier *et al.* 1993).

GEOLOGY OF IOS

Figure 2 is a simplified geological map of Ios. Figure 3 illustrates the gneiss dome geomorphology of the island and the basic structural relationships. There are two tectonostratigraphic units exposed on the island: 'basement' and 'series' (Henjes-Kunst 1980, Van der Maar 1980). The 'basement' augen-gneiss/leuco-gneiss core is fringed by garnet-mica schists and granitic gneisses. These contain metamorphosed mafic dykes and garnet-mica schist xenoliths. The 'basement' is tectonically overlain by the marble–blueschist 'series', a sequence of thick carbonate units with intervening schists and metamorphosed mafic lenses.

The domal geomorphology of the augen-gneiss 'basement' bears some resemblance to the core of the nearby Naxos M_2 migmatite complex (Jansen & Schuiling 1976, Urai *et al.* 1990, Buick 1991). However, on Ios there are: (i) no substantial metamorphic zonations like that of the Naxos migmatite dome; and (ii) Rb–Sr whole rock isochron ages of approximately 500 Ma pertaining to a pre-Hercynian pluton as the protolith to the augen-gneiss (Henjes-Kunst 1980, Henjes-Kunst & Kreuzer 1982, Andriessen *et al.* 1987).

Evidence for an M_0 pre-Alpine ($\sim$300 Ma) amphibolite facies metamorphism and/or magmatic phase within the Ios 'basement' has chiefly been drawn from isotopic data (e.g. 300–305 Ma for U–Pb on zircon, and 288–295 Ma for Rb–Sr muscovite-whole rock ages; Henjes-Kunst & Kreuzer 1982, Van der Maar & Jansen 1983, Andriessen *et al.* 1987). Subsequent Alpine events have almost completely erased other evidence for this M_0 event. The later Alpine metamorphic events are: M_1, HP–LT metamorphism which resulted in the formation of jadeite (Henjes-Kunst 1980), chloritoid and glaucophane (Van der Maar, 1981), and an overprinting M_2 Miocene greenschist facies metamorphism characterised by the growth of chlorite, albite, biotite and garnet (Van der Maar 1980, Henjes-Kunst 1980). Early K–Ar and Rb–Sr geochronological studies on Ios suggest Eocene ages

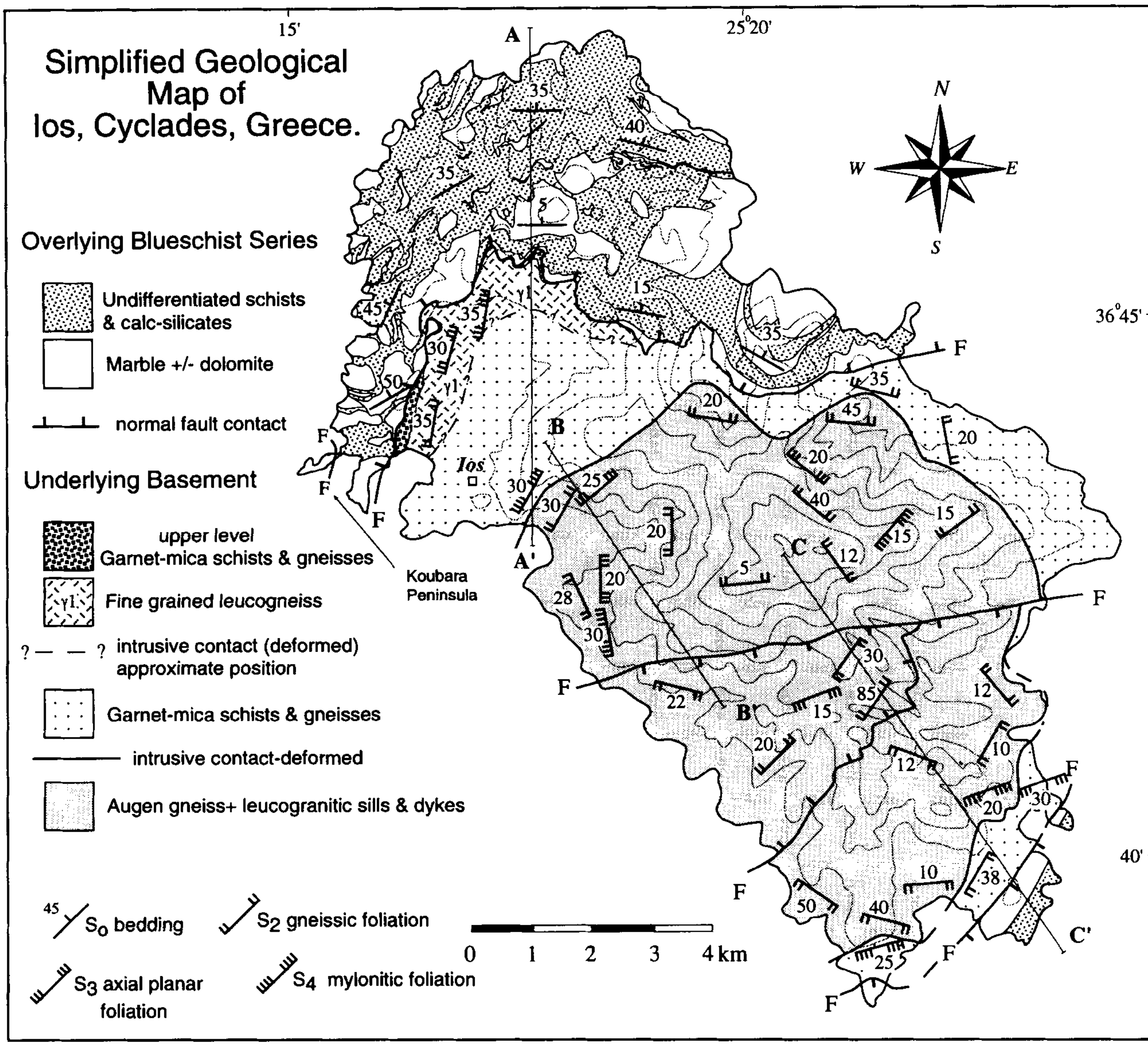

Fig. 2. A simplified geological map of Ios, Cyclades, Greece (including mapping by Van der Maar & Jansen 1981 and Grütter 1993).

(40–50 Ma) for M_1, and Oligo–Miocene ages (25–30 Ma) for M_2 (Kreuzer *et al.* 1978, Andriessen *et al.* 1979, Henjes-Kunst & Kreuzer 1982, Andriessen *et al.* 1987).

The overlying marble–blueschist 'series' constitute a metamorphic sequence of Mesozoic marbles, dolomites, calc-schist, quartzite schist, metapelitic and metabasic rock types. Several metabasic horizons preserving eclogitic and blueschist facies assemblages have been interpreted by previous workers, as metamorphosed ophiolites. This led to the suggestion that the 'series' is a tectono-metamorphic pile accumulated during Alpine collisional orogenesis (e.g. Van der Maar & Jansen 1983). Mineralogical assemblages within the 'series' indicate two distinct phases of Alpine metamorphism: Eocene M_1 blueschist/eclogite facies metamorphism, and Oligo–Miocene M_2 greenschist facies metamorphism (Henjes-Kunst 1980, Van der Maar 1980, Van der Maar & Jansen 1983, Andriessen *et al.* 1987). Pressure estimates for M_1 are 9–11 kbar, with temperatures ranging from 350–400 °C (Van der Maar & Jansen 1983). M_2 is estimated to have occurred at 5–7 kbar, with temperatures ranging from 380–420 °C (Van der Maar & Jansen 1983).

The exact nature of the contact between the pre-Alpine 'basement' and overlying blueschist 'series' units remains controversial. Van der Maar & Jansen (1983) suggest that: (i) the contact is a pre- or syn-M_1 thrust plane localised along an old erosional surface or unconformity; (ii) a layer of actinolitic schist at this position is an ophiolite sheet and is therefore the location of the thrust surface; and (iii) up to 100 m of schists above the ophiolite and beneath the first marble bed are part of the 'series'. Grütter (1993) disputes the significance of the Van der Maar & Jansen (1983) 'basement-series' contact and argues that the 'basal marble beds', intervening schists and metabasic rocks are infact part of the 'basement' stratigraphic succession. He suggests that an early-M_1 thrust higher in the stratigraphy separates the 'series' from the 'basement'. We suggest that both of these hypotheses are invalid, and that the contact (marginally

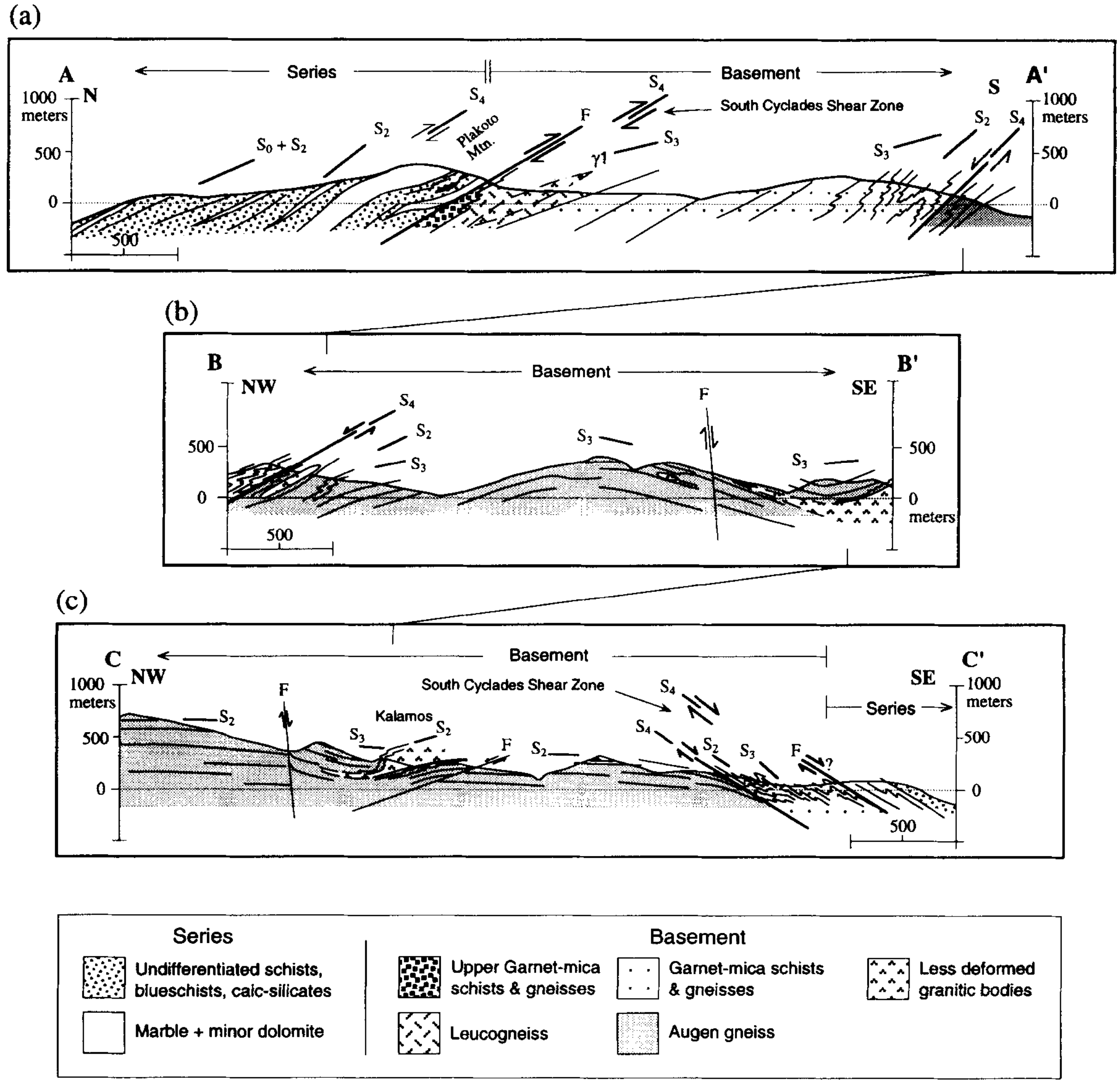

Fig. 3. (a), (b) and (c). Serial cross-sections through the Ios gneiss dome (refer to Fig. 2 for transect positions). The 'basement' (an augen-gneiss core fringed by garnet–mica schists and gneisses) is overlain by the tectonically emplaced marble–blueschist 'series'. D_1–D_4 generation fabrics and the 'basement-series' contact are domed (D_5) over the island.

above the position recognised by Van der Maar 1980) is a young normal fault that truncates marble beds of the 'series' and juxtaposes them against the underlying 'basement' complex (Fig. 3). This normal fault also truncates the South Cyclades shear zone, which defines the mylonitic carapace of the lower-plate (see below).

A third tectonic unit exposed on the Koubara peninsula was described by Van der Maar & Jansen (1981), and Van der Maar & Jansen (1983) as an allochthonous metabasic rock, metamorphosed in the greenschist facies and *thrust* against the 'series' (Fig. 2). Given that numerous low-angle normal faults dissect the pre-Hercynian 'basement' and overlying 'series' units, allochthonous rocks faulted against the 'series' unit would give weight to the suggestion that a detachment fault (Davis & Lister 1988) might be exposed. In our investigation, the metabasic rocks were found to be a minor constituent and we were not convinced of the existence of a detachment fault at the Koubara peninsula.

Apart from locally derived young sediments (Pliocene to recent), no other low grade or non-metamorphic rocks have been mapped on Ios.

STRUCTURAL ANALYSIS OF THE IOS BASEMENT

From reconnaissance work on Ios we distinguished the 'basement' and 'series' tectonostratigraphic units postulated by early workers. Detailed studies were then conducted within the 'basement' during which five generations of ductile structures (S_1–S_5) due to five phases of deformation (D_1–D_5) were recognized. It was also recognised that strains due to D_3 and D_4 are largely localised in mid-to-high structural levels and that at these positions earlier fabrics and structures (largely due to D_2) have been substantially modified and transposed. In the following section we first establish the typical structural characteristics and overprinting relationships in the 'basement', and then illustrate key geological aspects through key locality descriptions from several structural positions.

Structural relations at the augen-gneiss/garnet-mica schist contact

The contact between the augen-gneiss core and overlying garnet-mica schists at the northern point of the Milopotas beach area occupies a mid-level in the 'basement' complex (Fig. 4). At this location four of the five generations of ductile structures (S_1–S_4) can be readily identified. Excellent exposure enables the correlation of structures in the overlying garnet-mica schists with structures in the augen-gneiss; the prime factor in choosing this area as a key locality.

Garnet-mica schist S_1 *and* S_2 *fabrics.* Due to the intensity of later deformations, there is little information in regard to the nature of the D_1 deformation. A characteristic feature of the garnet-mica schists is quartz veins (generally sub-parallel to layering, S_0) that are commonly transposed and isoclinally folded. Relicts of S_1 can be recognized in the microlithons of the S_2 axial planar cleavage to these F_2 folds. In more micaceous rocks S_1 can sometimes be identified as decussate recrystallised white micas in the microlithons of the anastomosing S_2 schistosity (Fig. 5a). No mesoscopic folding is observed to which S_1 is axial planar.

F_2 quartz fold hooks are rootless folds with attenuated limbs and comparatively thicker hinge regions. Here, F_2 fold axes generally plunge moderately to the NNW. The anastomosing S_2 schistosity is a differentiated crenulation cleavage and it is sub-parallel to compositional layering (bedding S_0) in metasedimentary rocks. S_2 is the main penetrative foliation within the garnet-mica schists and in part defines the domal geomorphology of the 'basement' gneiss dome (Fig. 3). At this mid-level structural position within the 'basement', S_2 dips moderately to the NW.

L_2 is a striping and stretching mineral lineation. It is defined by smeared out grains of biotite, quartz or chains of cataclased feldspar fragments, as well as the alignment of pressure shadows adjacent to garnet porphyroclasts. Later D_3 co-axial refolding, D_4 transposition and reorientation of earlier structures has made field identification of L_2 lineations difficult.

S_2 *within the augen-gneiss.* The earliest recognisable fabric in the underlying augen-gneiss (as in several augen-gneiss horizons within the garnet-mica schists) is a penetrative, anastomosing, gneissic foliation. This gneissic foliation is sub-parallel to S_2 in the garnet–mica schists and together they are deformed by later events (hence the augen-gneiss foliation has been assigned to S_2). The S_2 gneissic foliation is a mylonitic foliation with a strong N–S oriented, mineral stretching and striping lineation (L_2). Foliation domains are generally 0.5–2 mm across and are defined by white mica grains and fine, dynamically recrystallised quartz and feldspar porphyroclasts. The spacing between folial domains is dictated by the size of feldspar porphyroclasts (2 mm–4 cm), and is generally a function of the size of the original phenocryst and degree of grainsize reduction (due to ductile and cataclastic deformation). The L_2 lineation is defined by the alignment of debris trails and pressure shadow regions around feldspar porphyroclasts, elongate quartz grains, and the preferred alignment of micas.

S_3 *and* S_4. S_2 in the augen-gneiss and garnet-mica schists is folded by inclined F_3 (D_3) fold packages. F_3 fold packages are found throughout the 'basement' and vary from tight to isoclinal in higher structural levels to quite open structures at deeper levels. Asymmetric, disharmonic F_3 fold packages vary from 10 cm–50 m in scale. The S_3 foliation is a differentiated crenulation cleavage but is generally non-penetrative. At this location S_3 crenulations have developed in the axial zones of tight F_3 folds. These crenulations dip shallowly to the NW and are overprinted by M_2 greenschist facies minerals (Fig. 5b). The respective F_3 fold axes are sub-parallel to mineral stretching and striping lineations (L_2 and L_4), and plunge shallowly to the north. It should be noted however, that in the lower structural levels (e.g. the south-central region of the augen-gneiss core) F_3 folds are broader and fold axes trend more to the NE–SW (e.g. between 230–190°). At these deeper levels, L_2 mineral stretching lineations plunge steeply towards the NW or SE.

Where found together, mesoscopic D_4 structures overprint D_3 structures as well as M_2 greenschist facies minerals (e.g. Figure 5c). Within the garnet–mica schists and gneisses, D_4 structures are: (i) discontinuous shear bands and shear band foliations, spaced approximately 1.5 to 10 cm apart (i.e. *C*-surfaces of Berthe *et al.* 1979); (ii) symmetric/asymmetric extensional crenulation cleavages 0.5 to 1.5 cm in scale (Fig. 5c, see Platt & Vissers 1980); (iii) 5 cm to 2 m scale symmetric/asymmetric foliation boudinage within schist and gneissic layering (*op. cit.*); and (iv) 5 cm to 1.5 m scale layer boudinage.

Within the augen-gneiss, mesoscopic D_4 generation structures are: (i) discrete shear bands (<10 cm wide) and shear zones (generally <5 m wide); and (ii) localised shear zones, small faults and breccia zones associated with the development of 1 to 3 m long, symmetric/asymmetric foliation boudinage structures (Fig. 5d). Mesoscale D_4 structures possess N–S trending mineral-stretching lineations and are generally associated with macroscale top-to-the south or north shear zones. Locally, the dominant asymmetry of D_4 structures at this northern contact shows that structurally higher levels have moved to the north. At the equivalent contact exposed in the south of the island, the D_4 shear sense is south directed.

S_5 *structures.* Fabrics associated with the fifth generation of structures are not pervasively developed and were not found at this locality. Recognised elsewhere, they are seen as N–S striking, vertically dipping crenulations of earlier fabrics and close spaced fractures in feldspars in granitic gneisses. S_5 foliations are also developed as axial planar fabrics to rare, north–

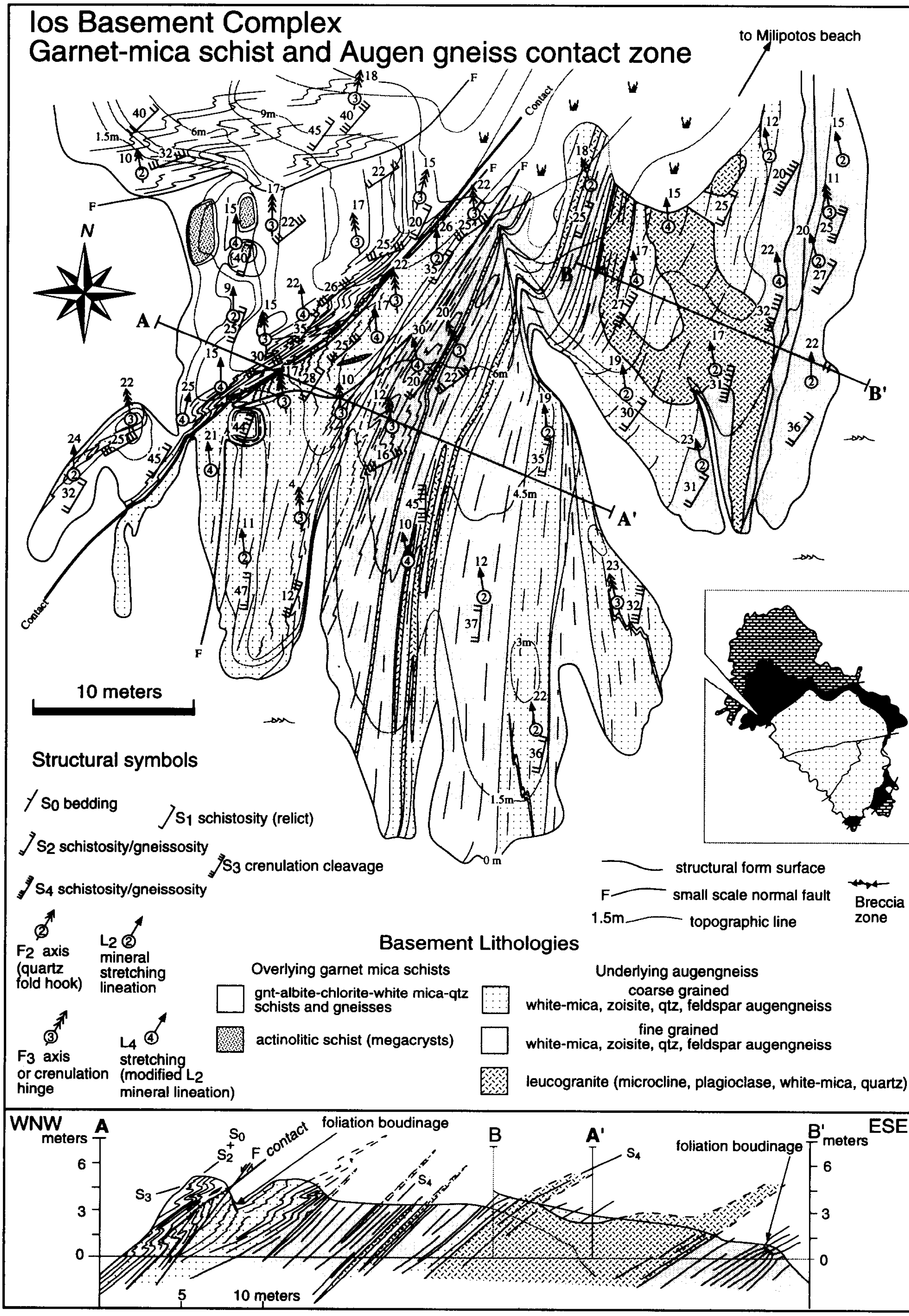

Fig. 4. Map of the Ios basement garnet–mica schist/augen-gneiss contact zone exposed at the northern point of the Milipotos beach area. Four of the five generations of ductile structures can be identified at this key locality. The original intrusive contact has been locally folded (D_3) and later partially decoupled (D_4).

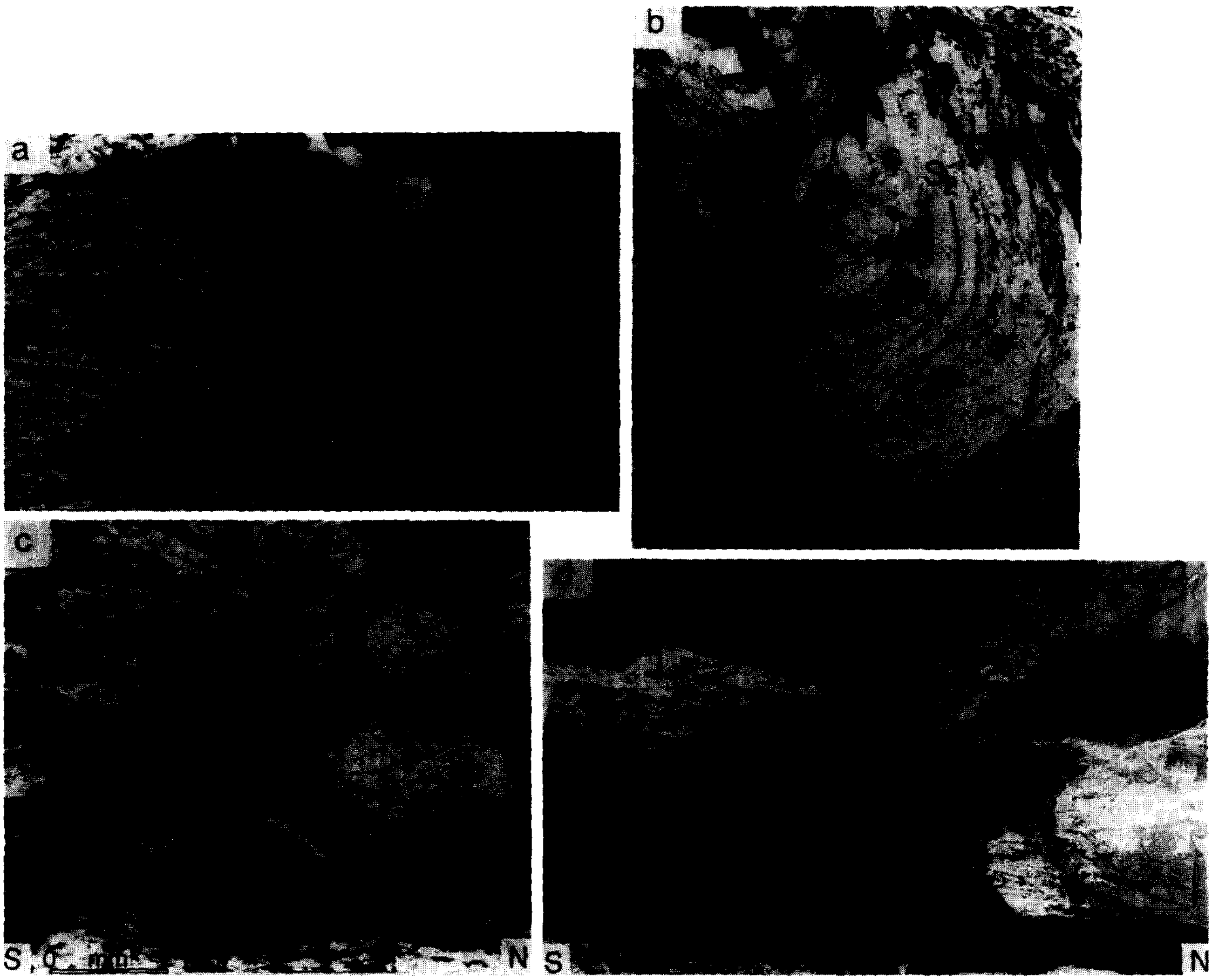

Fig. 5. (a) S_1 in microlithon regions of the S_2 foliation as decussately recrystallised white mica. S_2 deflected around (pre-D_1?) M_0 garnet (gt). (b) M_2 albite (alb) overprinting a F_3 microfold hinge in a garnet–white mica–quartz–albite schist. (c) Post-M_2 D_4 extensional crenulation cleavages cut S_2 (and subparallel S_3) in a garnet–white mica–quartz–albite schist. Top south shear sense. (d) D_4 asymmetric foliation boudinage in augen-gneiss; viewed perpendicular to the north plunging L_4 stretching lineation. Shear sense top-to-the south.

Fig. 6. (a) From Locality 1, Fig. 7. Northern end of an ovoid body of relatively undeformed granite (protolith to the augen-gneiss). Deformation intensity increases away from the body, and is seen as the progressive formation of a mylonitic foliation and a N–S oriented mineral stretching lineation. Shear sense is symmetrically disposed around the body. Inset box: the location of (b). (b) Detail showing undeformed protolith and top-to-the north shear sense for D_4 shear bands which displace S_2 foliation. Scale: pencil = 15 cm. See inset box in (a) for location. (c) Type 1 S–C mylonite, augen-gneiss. Feldspar 'pull-apart' augen (K.felds) with dynamic recrystallisation, thinning and necking in the pull-apart region. S–C relationships defined by anastomosing bands of feldspar debris, white mica grains and dynamically recrystallised quartz. Top-to-the north shear sense.

south trending, upright, open folds (F_5) of between 2 to 3 m in amplitude (generally found in the southwest of the island). While larger folds of this generation exist over the scale of the island, the mesoscale F_5 folds are probably parasitic and associated with north–south elongate D_5 doming and warping of the 'basement' complex. Similarly, pervasively developed N–S striking, vertically dipping joint sets probably contribute towards defining the domal geomorphology of the 'basement' complex.

Deformed granitoids and the origin of the augen-gneiss foliation

From deeper levels within the augen-gneiss complex, granitic remnants ranging in diameter from 5 cm to 5 m display marked variations in strain and provide three dimensional views of deformed granitoids in shear zones (e.g. Figure 6). Figure 7 is a map of an area where several granitic bodies can be found. The ovoid granitic body of Fig. 6 is a lenticular domain enveloped by the S_2 mylonitic foliation and asymmetric D_2 and D_4 shear band foliations.

At the ends of the body, strain increases within a few meters from the undeformed protolith to where there is a mylonitic augen-gneissic foliation indistinguishable from the surrounding gneissic foliation. Grain-size reduction of feldspar augen has been achieved through dynamic recrystallisation and cataclasis (see also Fig. 6c). Biotite porphyroclasts are smeared out and a strong N–S oriented mineral lineation is observed. Clearly, this granitic rock (and several others like it) does not have an intrusive relationship with respect to the surrounding augen-gneiss ('γ5' of Van der Maar & Jansen 1981).

Leucogranitic sills and dykes

Deformed dykes and sill-like leucogranitic bodies (generally less that 5 m in width) occur throughout the 'basement'. Leucogranitic dykes cross-cut and truncate the S_2 mylonitic foliation of the augen-gneiss and sill-like bodies possess an intense mylonitic fabric coplanar to both S_2 and S_4. Typically, heterogeneous distribution of D_4 mylonitization and transposition (parallel to favourably oriented D_2 fabrics) results in folding of cross-cutting leucogranitic dykes. These folded dykes are invariably characterised by fold axes parallel to the L_4 mineral extension lineation, and mylonitic axial-planar foliations that define S_3 and S_4. Rarely, dykes can be followed into the transposed sills. In general, internal mylonitic foliation in leucogranitic sills is related to D_4 shear zones in which S_4 is intensely developed.

These observations suggest late stage intrusion of the leucogranites (post-D_3/F_3 folding, pre- to syn D_4 formation of the younger shear zones). Rb–Sr isotope analysis of white mica from one such leucogranitic sill by Henjes-Kunst & Kreuzer (1982) yielded an age of 13 Ma (see their Fig. 2, sample 77-227). From this they inferred the effects of the regional late Miocene thermal event due to granitoid intrusion. We would also infer a late Miocene thermal event and/or time of operation for the D_4 shear zones that dissect the 'basement'.

The 'basement-series' contact

Work by Banga (1983) and detailed mapping through the region immediately north of the Port of Ios and in the south of the island reveals that: (i) a zone of intense D_4 ductile shear with a minimum thickness of approximately 200 m has been truncated in its upper structural levels by a large scale normal fault; and (ii) this normal fault separates lower-plate 'basement' rocks from upper-plate 'series' rocks.

The D_4 ductile shear zone is referred to as the 'South Cyclades' shear zone. Within the shear zone, S_2 is still pronounced, but is folded by tight, disharmonic F_3 folds. While F_3 fold axes typically trend north–south and are parallel to the L_4 mineral stretching lineation, there are several examples of extreme non-cylindrical folding. Sheath-like folds were also observed with long axis parallel to L_4 (Fig. 8, locality 1). In F_3 hinge regions, intense axial planar S_3 crenulation cleavage is also developed. S_2 and S_3 fabrics are overprinted by D_4 C-surfaces which display a consistent top-to-the south shear sense and gradually die out down section. In the north of the island the South Cyclades shear zone is a north-dipping, south-directed ductile shear zone with an apparent thrust geometry (see also Fig. 3). In the south of the island the South Cyclades shear zone outcrops as a south-dipping, south-directed ductile shear zone (i.e. normal sense). The penetrative D_4 fabrics in the two zones indicates that the same sense of shear and S_4, together with the S_2 and S_3 fabrics, are folded over the intervening arch with little change in their angular relationships.

In the northern Plakoto mountain region, a leucogranitic gneiss (identified by Van der Maar & Jansen 1981 as 'γ1') constitutes part of the South Cyclades shear zone. The gneiss displays a penetratively developed mylonitic foliation which can be traced into the axial zone of tight F_3 folds in the surrounding country rock (e.g. Fig. 8 location 2). Together, the country rock (a package of garnet–mica–albite schist, quartzites, quartzitic and actinolitic schists) and granitic gneiss are faulted against hanging-wall marble beds (Fig. 3a). The overlying marble beds similarly truncate at the fault (Fig. 8 locality 3) and are disrupted by numerous small-scale normal faults. Thick breccia consisting of chloritic fragments of both the underlying and overlying units (<0.5 m thick), together with quartz and calcite veining are observed along its length.

The relationships described above preclude the notion of a continuous stratigraphic succession at this structural level (Grütter 1993). The presence of a major fault, the change in rock types and structural discordance across this fault leads us to conclude that it represents a young structural discontinuity between underlying 'basement' and overlying 'series'. We suggest that the 'basement' and 'series' have been juxtaposed late in the history of their tectonic evolution by the South Cyclades shear zone, and

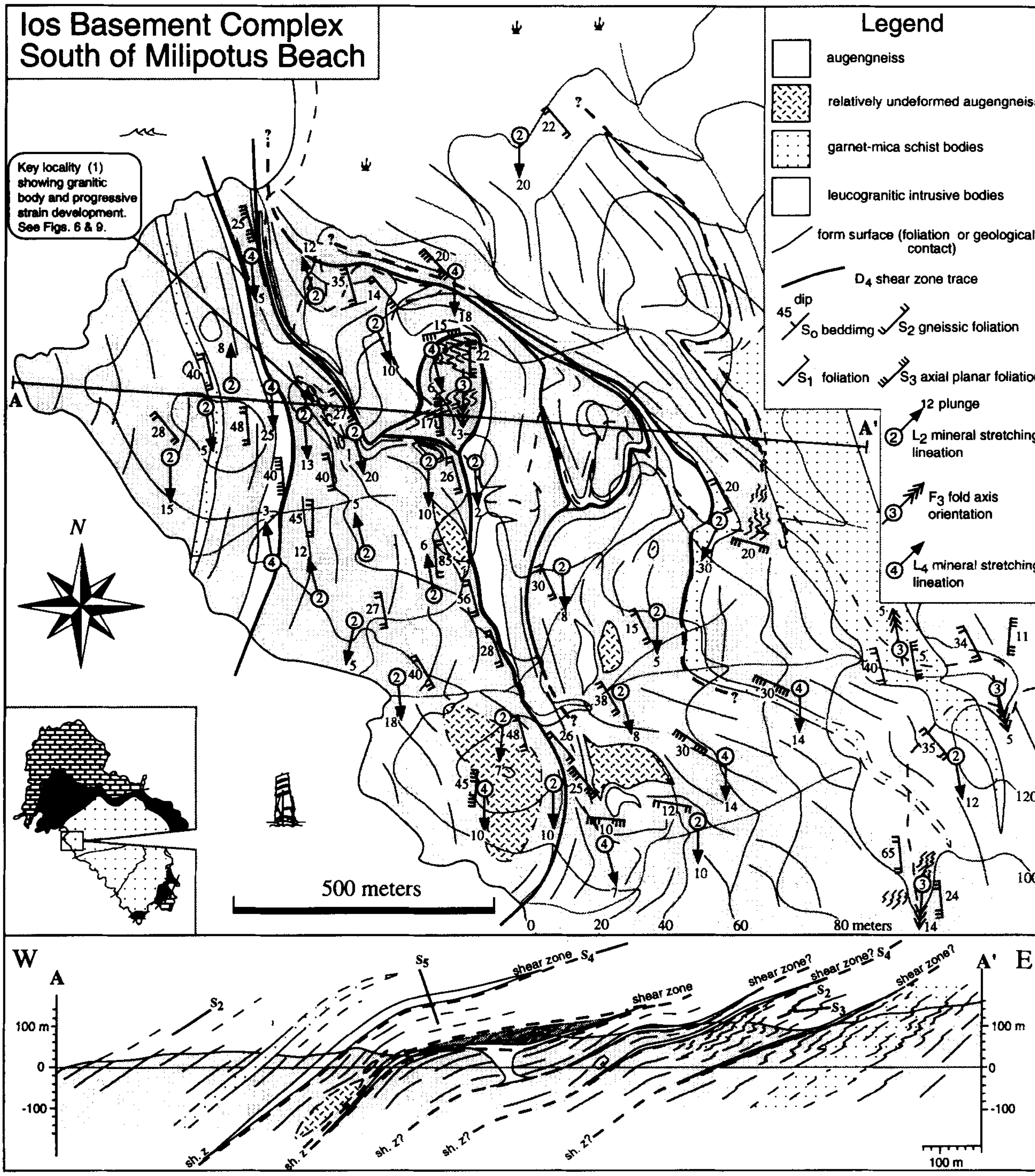

Fig. 7. Augen-gneiss complex structurally below the garnet–mica schist/augen-gneiss contact. Leucogranitic dykes and sills are transposed ('smeared out') in D_4 shear zones, less deformed granitic bodies (granitic 'augen') are enveloped by S_2 and S_4, and late near-upright N–S trending folds (S_5) warp all earlier generations of structures.

that substantial portions of both units have been removed during final juxtaposition by extensive faulting. Late stage warping (D_5) has subsequently deformed the 'basement-series' contact and resulted in a north-dipping fault contact in the north of the island, and a south-dipping fault contact in the south of the island. Four lines of evidence however, lead us to conclude that the contact was a south-dipping normal fault: (i) late stage normal faulting is ubiquitous throughout the overlying 'series' unit; (ii) on Mykonos, Naxos and Paros there is kinematic coordination between the movement sense of earlier Miocene ductile shear zones and later normal faulting (i.e. we infer that top-to-the south Miocene shearing on Ios evolved into top-to-the south normal

Fig. 8. Northern exposure of the Ios 'basement-series' contact. Highly strained meta-sediments and meta-intrusive rocks in the upper levels of the 'basement', deformed during the operation of a major D_4 shear zone (South Cyclades Shear Zone: see Fig. 3a) have been truncated at a normal fault contact with the overlying marble-schist 'series'. Bedding in the 'series' (defined by distinct marble units), similarly terminates at the fault contact (see form surface traces: locality 1). Other key localities are referred to in the text. In this region the normal fault contact has been rotated into an apparent thrust geometry (hanging-wall up).

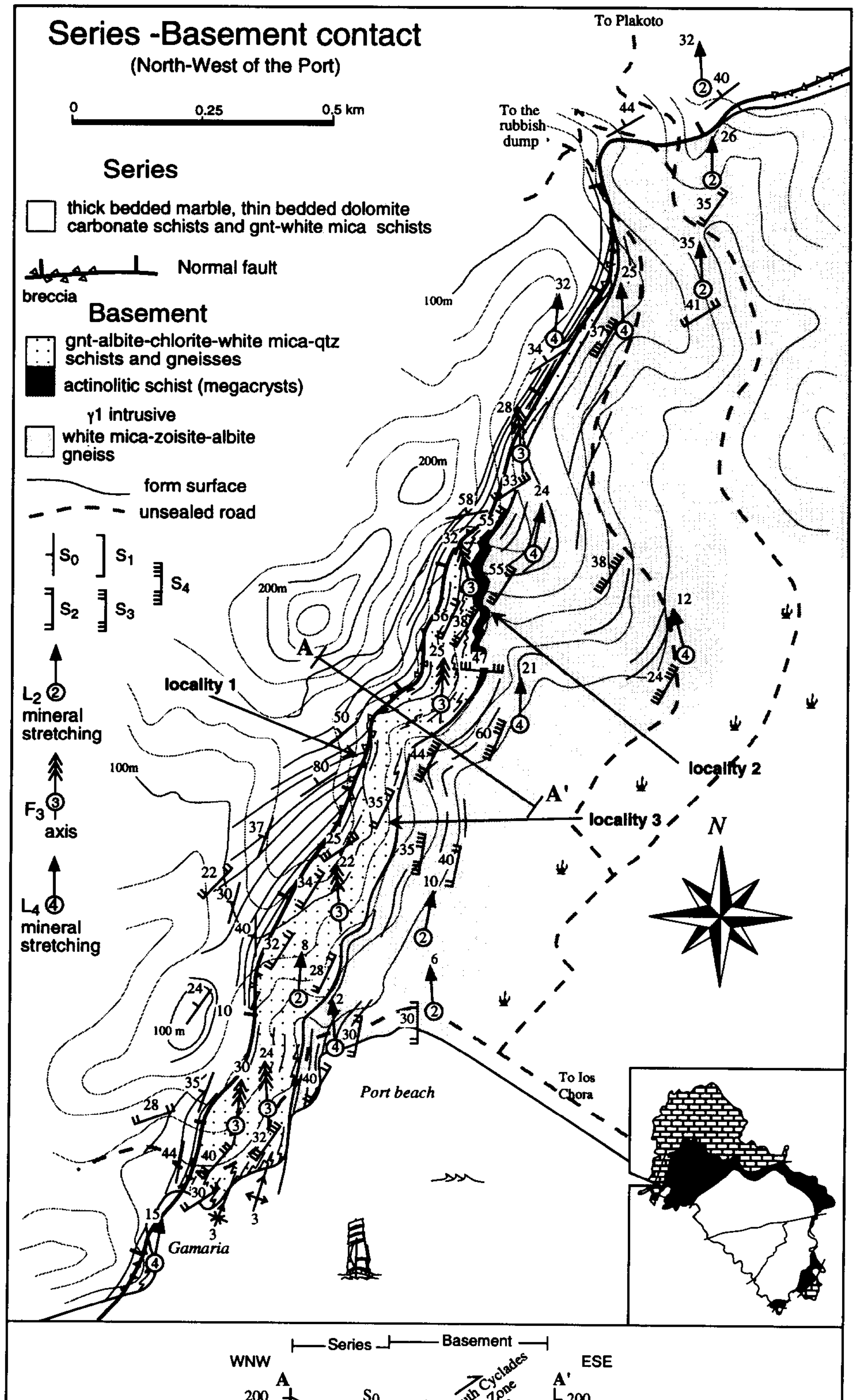
Series -Basement contact
(North-West of the Port)
0 0.25 0.5 km
Series
thick bedded marble, thin bedded dolomite carbonate schists and gnt-white mica schists
Normal fault
breccia
Basement
gnt-albite-chlorite-white mica-qtz schists and gneisses
actinolitic schist (megacrysts)
γ1 intrusive
white mica-zoisite-albite gneiss
form surface
unsealed road
S0 S1 S4 S2 S3
L2 mineral stretching
F3 axis
L4 mineral stretching
To Plakoto
To the rubbish dump
locality 1
locality 2
locality 3
Port beach
Gamaria
To Ios Chora
N
Series Basement
WNW ESE
200 meters
100
0
S0 S2 S3 S4 F S2 & S4
South Cyclades Shear Zone
Normal fault rotated into an apparent thrust geometry.

Fig. 8.

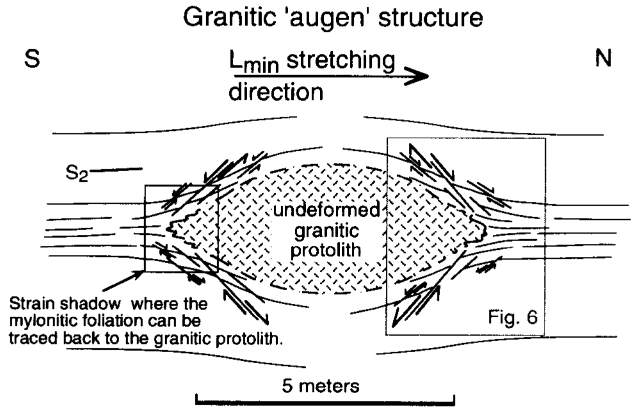

Fig. 9. Schematic diagram of a granitic 'augen' structure found in the Ios 'basement' complex (e.g. Figure 6). Shear sense varies systematically around the body, and at the ends of such bodies (pressure shadow regions) the mylonitic foliation can be seen to have formed from a granitic protolith (for location see Fig. 7, locality 1).

faulting); (iii) the preservation of eclogitic facies mineral assemblages in 'basement' garnet–mica schist tentatively indicates that 'basement' rocks were deeper than the overlying 'series' rocks (implying exhumation of 'basement' rocks from beneath the 'series' through the operation of normal sense shearing and faulting); and (iv) the area was subject to regional continental extension from at least the mid-Miocene onwards.

DISCUSSION

Pre-Alpine, Eocene and Miocene fabrics

By integrating our structural, metamorphic and geochronological data we distinguish three main phases of fabric generation in the tectono–metamorphic evolution of the Ios 'basement' complex: (1) a pre-Alpine phase; (2) an Alpine collisional phase (mainly Eocene); and (3) fabrics related to Miocene extension and younger events.

Pre-Alpine fabrics. Previous workers attribute the formation of the augen-gneissic foliation (S_2) in the 'basement' core to the M_0 Hercynian (300–295 Ma) amphibolite facies metamorphism (e.g. Henjes-Kunst & Kreuzer 1982). This study is yet to find fabric or textural relationships that link the M_0 event to the formation of the S_2 augen-gneissic foliation. The earliest fabric recognised is rarely preserved and found only within the microlithons of decussately recrystallised (white mica dominated) S_2 fabrics (Fig. 5a). As such, little can be discerned about the kinematics and tectonic significance of these D_1 fabrics.

Alpine collisional fabrics (mainly Eocene). The penetrative nature of the mylonitic S_2 augen-gneiss foliation (and S_2 schistosity in the garnet–mica schists) over the exposed thickness of the 'basement' (approximately 2.5 km), indicates that the D_2 deformation was on a crustal scale. Several observations indicate that D_2 occurred in response to the Alpine collisional orogeny. Specifically, the S_2 schistosity in the garnet–mica schists anastomoses around the large M_0 garnet porphyroblasts (i.e. S_2 is post-M_0), and M_1 Eocene Alpine blueschist and eclogitic facies mineral assemblages in garnet–mica schists and deformed 'basement' mafic intrusions define S_2 and L_2 fabrics. In this context it should be noted that D_2 has produced strong glaucophane lineations in the 'series', suggesting that D_2 took place subsequent to mineral growth during Eocene high pressure metamorphism. However, since these assemblages were stable during deformation, it is inferred that D_2 also took place under high pressure conditions.

D_2 kinematic indicators are not easily distinguished. S_2 foliations (*S*-surfaces) generally anastomose around feldspar augen with no apparent asymmetry. The development of D_2 *S–C* relationships and shearband foliations are not as pronounced as those in D_4 shear zones, and at higher structural levels they can be confused with the effects of D_4 overprinting and transposition. At lower levels, L_2 mineral stretching lineations and S_2 foliations with distinct *S–C* relationships are localised at the margins of large, relatively undeformed igneous bodies. From our recognition that ductile shearing can vary in shear sense around less deformed granitic bodies (e.g. the granitic 'augen' in Fig. 9), we view the kinematic significance of these discrete non-coaxial simple shear zones with caution. Our observations are similar to those of Choukroune & Gapais (1983) and Castro (1986) who show that areas of granitoids can remain relatively undeformed while heterogeneous strain is partitioned into discrete zones. The mesoscale variation in shear sense around the granitic bodies lends some credence to the hypothesis that the shear zones are ductile zones between less deformed 'augen' (e.g. Bell 1978). By analogy, these 'augen' structures in the Ios 'basement' are also not dissimilar to the tectonic lenses of non-mylonitized rock in crustal scale zones of non-coaxial laminar flow, described by Davis *et al.* (1987).

The general absence of asymmetric D_2 kinematic indicators could suggest that D_2 fabrics formed in a regime of coaxial laminar flow. Such a regime may have been induced by lithostatic loading during Alpine collisional orogenesis and subsequent (hypothetical) gravitational collapse of the orogenic belt. However, we do not regard the absence of kinematic indicators in itself as an indication of a coaxial D_2 deformation.

Fabrics related to Miocene extension. D_3 folds initiated prior to or during the onset of M_2 greenschist facies conditions, and these conditions continued on through the formation of D_4 mylonites and the localisation of high shear strains. While D_3 and D_4 could be related to the same single phase of progressive deformation, two observations suggest that D_3 and D_4 are distinct generations of deformation: (i) D_4 structures always overprint D_3 structures; and (ii) M_2 porphyroblasts overprint D_3 structures but are deformed by D_4 structures. Nevertheless, from the preservation of microstructures typical of dynamic recrystallisation (Urai *et al.* 1986), we infer that the D_4 deformation generally outlasted the M_2 metamorphism and M_3 intrusive events. Therefore, as the M_2 and M_3 events span mid–late Miocene times, we would also infer that the D_3 and D_4 deformations are Miocene in age.

Where zones of high D_4 shear strain are recognised (10–500 m scale), an analysis of kinematic indicators leads to the conclusion that they were zones of non-coaxial laminar flow (see also Banga 1983). These kinematic indicators include *S–C* fabric relations, asymmetric mica 'fish' and oblique foliations in dynamically recrystallised quartz (Lister & Snoke 1984), asymmetric pressure shadows around feldspar porphyroclasts and M_0 garnet porphyroblasts, and quartz *c*-axis fabrics.

Heterogeneous distribution of D_3 and D_4 strains are also reflected by the pattern of lineation orientations. Figure 10 is a simplified lineation diagram of L_2, L_4 and F_3 fold axes in the 'basement' complex at different structural levels. The lineations define a general N–S trend which is warped over the structure. However, at deeper structural levels (Fig. 10e) the lineations are markedly divergent from the N–S lineation trend of higher levels; L_2 lineations plunge steeply NW while F_3 fold axis trend SW–NE. Based on our observations, localised younger D_4 shearing (e.g. in higher structural levels) has apparently reoriented older L_2 lineations to be colinear with the D_4 N–S lineation trend. Reorientation of older lineations and structures by a younger penetrative shearing is not uncommon (e.g. Bell 1978, Ghosh & Sengupta 1987).

It should also be noted that from descriptions given

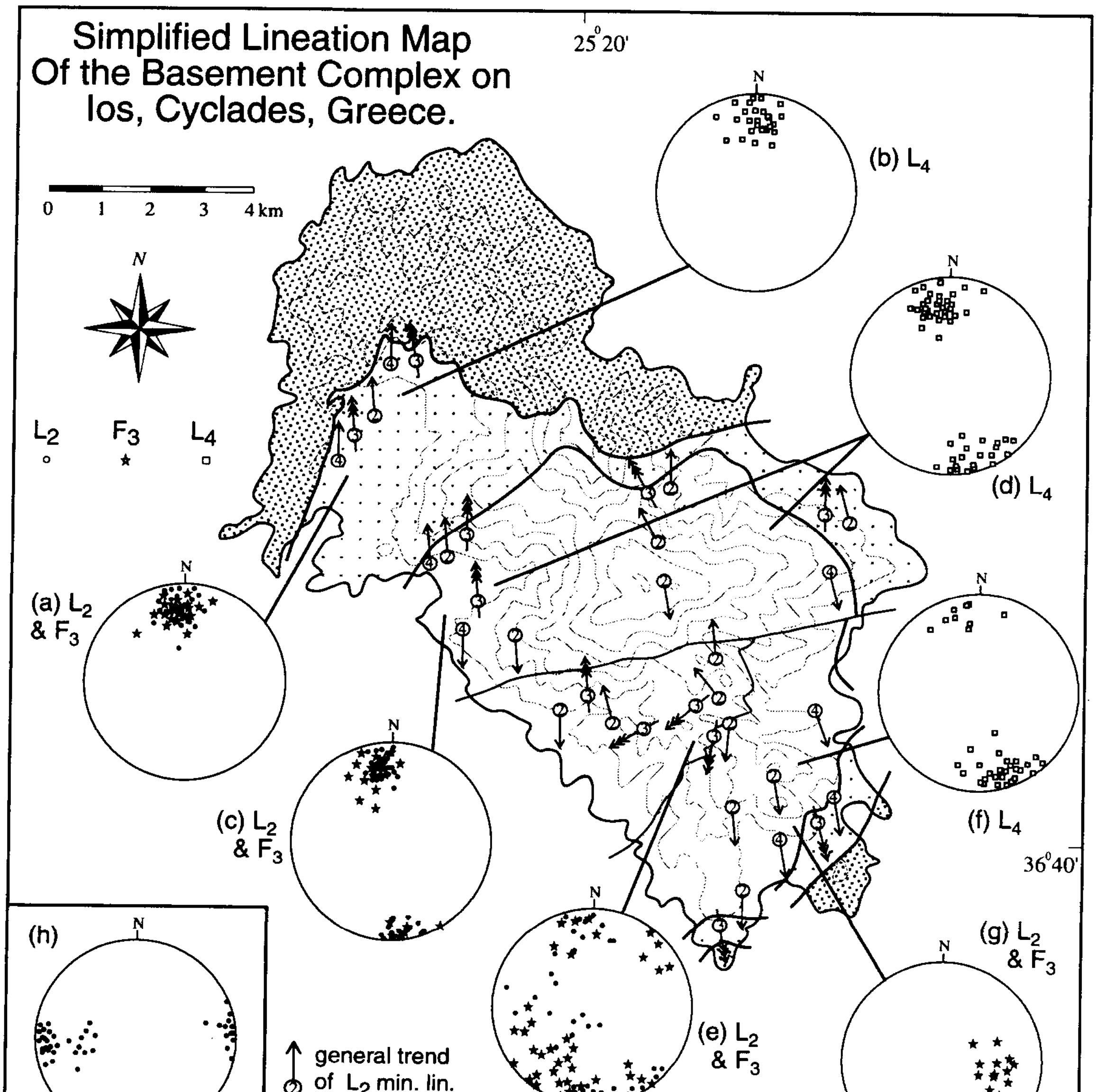

Fig. 10. (a)–(g) Simplified lineation map of the Ios Basement Complex showing lineation patterns with respect to structural position, over and through the domal geomorphology of the island. (a) and (b) Highest levels north end. (c) and (d) Mid-level, north end. (e) Lowest level, exposed Ios south-central. (f) and (g) Mid-to-high levels, south end. (h) Poles to S_5 foliation taken throughout the basement.

previously, late-Miocene D_4 shear strains have localised in and around granitic sills. Davis *et al.* (1982) described a similar relationship and suggested that the leucogranitic sheets could have acted as preferential strain guides due to their favourable orientation and quartz rich compositions. It could also be that D_4 ductile deformation tended to localise within thermally weakened and favourably oriented sills and their surrounding country rocks (Lister & Baldwin 1993, Scott & Lister 1992).

Miocene kinematics of the basement and formation of the Ios domal structure

The kinematics of the macroscale D_4 shear zones are complicated and Fig. 11 is a simplified diagram showing the position and sense of shear zones within the Ios 'basement'. There are as yet no relationships to indicate whether one sense of shear was followed by the opposite sense of shear during D_4. Conversely, there are meso- and microscale observations (see also Gautier & Brun 1994) which suggest that both senses of shear can operate in a zone dominated by either asymmetric or symmetric stretching (e.g. Figure 9). A tentative analogy could be made between the granitic 'augen' 'floating' in a ductilely deforming rock mass and the augen-gneiss core 'floating' in the 'basement' complex as a whole. However, unlike a granitic 'augen' structure the 'basement' complex is a composite (made up of many different rock types), and the same mechanical principles probably do not apply.

Gautier & Brun (1994), while acknowledging that shear sense on Ios is dominantly top-to-the south, proposed that formation of the Ios dome resulted from lower-plate ductile accommodation (beneath a north dipping detachment) of upbending of the brittle upper-plate (their Fig. 7). This hypothesis invoked a process of lower-plate back-rotation and localisation of the opposite sense of shear (southsense) on the southern flank of the forming dome, and bore some resemblance to the Reynolds & Lister (1990) model for the formation of the Cordilleran metamorphic core complexes of North America. The Reynolds & Lister (1990) model however, described late stage antithetic shear zones that formed in response to the folding and warping of the upper portions of a crustal scale extensional shear zone. The kinematically inactive mylonites of the main shear zone (at or above the brittle–ductile transition) still largely defined the domal geomorphology of the core complexes. For Ios, it is yet to be determined whether overprinting criteria can be found that suggest late stage antithetic shearing in response to dome formation. There are however, difficulties in applying the Gautier & Brun (1994) model to the Ios dome. This is particularly evident where the 'shear domains' of Gautier & Brun (1994) cut across the post-D_4 'basement-series' tectonic boundary and are apparently unaffected. In contrast to Gautier & Brun (1994), we suggest that synthetic and antithetic shear zones represent the partitioning of deformation in the ductiley flowing crust, with localisation of shear strains around pre-existing structures or contacts in the extending rock mass. Our work suggests that the simplest assessment of the D_4 movement picture is that the south-sense South Cyclades shear zone is the main structure localising crustal-scale, N–S ductile extension. If the Reynolds & Lister (1990) model is to be presented as a viable alternative, then it is more likely that the top-to-the north shearing observed at the northern augen-gneiss and garnet–mica schist contact is representative of a late stage antithetic shearing event.

With regards to the Ios structure then, the folding of the capping south-directed D_4 South Cyclades shear zone over the island indicates that dome formation could not have been early D_2 (Van der Maar & Jansen 1983); it must have been post-D_3 and/or post D_4. Though few S_5 foliations were recorded (N–S trending, upright—see Fig. 10h), we suspect that the combined effects of E–W directed D_5 shortening and late stage normal faulting and jointing contributed significantly to the doming of the 'basement' complex around a more competent augen-gneiss core. These observations are consistent with those made on Naxos of late stage warping of the Miocene shear zones due to E–W directed shortening (Urai *et al.* 1990, Buick 1991).

Top-to-the south versus top-to-the north directed Miocene ductile shearing

Several observations suggest a close temporal relationship between north to northeast directed shearing on islands to the north of Ios (Naxos, Paros and Mykonos: Urai *et al.* 1990, Faure *et al.* 1991, Lee & Lister 1992, Gautier *et al.* 1993), and south directed shearing of the Ios 'basement'. On Naxos, a late Miocene granodiorite (12.5 Ma: Wijbrans & McDougall 1988) was deformed in a top-to-the north crustal scale shear zone (Urai *et al.* 1990), and on Paros, top-to-the north shearing is inferred to have occurred in the same late Miocene north-sense

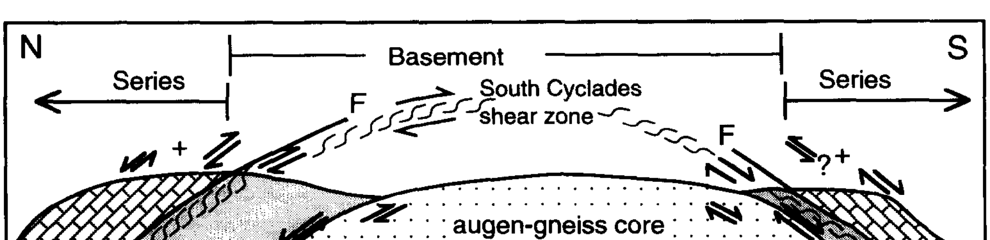

Fig. 11. Schematic diagram of the distribution and shear sense of macro-scale D_4 shear zones over the Ios complex.

shearing (Lee & Lister 1990, Gautier *et al.* 1993). Similarly, on Mykonos a biotite–hornblende granite intruded and was deformed by a top-to-the northeast shear zone at approximately 10–12 Ma (Faure *et al.* 1991, Lee & Lister 1992). Clearly, the region to the north of Ios was dominated by top-to-the north to northeast late Miocene shearing while Ios was subjected to top-to-the south D_4 shear zones.

Normal faulting due to continued extension processes in the region also reflect this dichotomy in movement sense. On several Cycladic islands north of Ios, mid-to-lower crustal rocks were finally juxtaposed beneath lower grade rocks by top-to-the north, low angle normal faults (Urai *et al.* 1990, Buick 1991, Lee & Lister 1992, Gautier *et al.* 1993). In the region around Ios, top-to-the south normal faulting was active. A regional synthesis of reflection profiles by Mascle & Martin (1990) also shows large scale normal faults with opposite senses of movement to the north and south of Ios.

These relationships could be taken to suggest that the Miocene was a period of bivergent extension in the Aegean. A similar hypothesis has been made for the neighbouring Menderes massif, to the east of the Attic–Cycladic metamorphic belt (Hetzel *et al.* 1995). However, unlike that of the bivergent Menderes core complex, in the Aegean a hypothetical central core is not anywhere exposed. The regional fault reconstructions by Mascle & Martin (1990) can only be taken as superficial evidence in support of the bivergent extension model. Furthermore, each of the hypothetical 'flanking' shear zones in the Aegean appears to have formed core complexes as the result of being bowed into elongate domal shapes. It is therefore not possible to demonstrate a bivergent mode of Miocene extension in the Aegean in the same way that has been done for the Menderes massif.

Owing to the scale of the deformations exhibited on Ios and neighbouring Sikinos (Banga 1983), it is considered unlikely that top-to-the south shearing on these southern Cycladic islands is simply antithetic to an overall top-to-the north regional shearing. It could be, however, that vital field evidence showing the overprinting of a period dominated by one sense of shear by a subsequent period of opposite shear sense has been missed. Current detailed geochronological analysis may yet resolve this point. Nevertheless, several regional correlations and inferences can still be made at this stage. In this contribution the juxtaposition of the Ios 'series' above 'basement' rocks is considered to have been accomplished through the operation of the south-directed South Cyclades shear zone and kinematically coordinated normal faulting. The metasedimentary rocks of the Ios 'series' possess strong affinities with rocks on Naxos and Paros which have been subjected to north directed shearing. Zones of penetrative north directed shearing are also found in the Ios 'series'. This might be taken to suggest that locally, north directed shearing preceded juxtapositioning by the operation of the south directed, South Cyclades shear zone and normal faulting (Fig. 12). This finding is still, however, somewhat at odds with the synkinematic granitoid age data outlined above.

Tectono–metamorphic significance of the Ios metamorphic core complex

Broadly then, the tectono–metamorphic history of the Ios metamorphic core complex involves the overthrusting of pre-Alpine 'basement' by the high pressure rocks of the Cycladic blueschist belt (north directed; Grütter 1993). The intrusion of an as yet undetermined volume of granitoids during the Miocene (indicated by the intrusion of syn-kinematic D_4 leucogranitic sills and dykes) could have contributed heat towards M_2 greenschist metamorphism (initiating D_4 deformation) and/or provided a Post-M_2 transient heat source during late-D_3/early-D_4 deformation. Thereafter, the overthrust pre-Alpine 'basement' was exhumed from beneath the 'series' rocks through the operation of the D_4 South Cyclades ductile shear zone.

In most respects the Ios gneiss dome closely resembles the core complexes of the Cordilleran U.S. extensional corridor (see Davis & Lister 1988): it is a structural dome over which stretching lineations and mylonitic fabrics (formed in large scale shear zones) have been warped, it possesses a core of igneous and metamorphic rocks, exhumation of the core (after it had been deeply buried during D_2 Alpine collision) was accompanied by igneous activity (syn-D_4 leucogranitic intrusives), and ductile deformation continued as temperatures decreased. However, the Ios 'basement' gneiss dome does not possess two critical relationships normally attributed to metamorphic core complexes: (1) an upperplate of brittlely disrupted, low grade or unmetamorphosed and/or old-metamorphic rocks juxtaposed against lower-plate ductilely deformed igneous and metamorphic rocks; and (2) the upper and lower-plates of the Cordilleran core complexes are separated by regionally extensive low-angle normal (detachment) faults.

To date, no such non-metamorphic or old-metamorphic apron has been discerned on Ios. Nevertheless, there are several neighbouring Cycladic islands which do possess an upper-plate of non-metamorphic rocks in normal fault contact with a lower-plate metamorphic unit (e.g. Naxos: Urai *et al.* 1990, Buick 1991; and Paros: Lee & Lister 1992, Gautier *et al.* 1993). The lower-plate units of these islands have strong affinities to the rocks of the Ios 'series'. It could conceivably be argued then that on Ios, a non-metamorphic upper-crustal apron overlying the 'series' has been eroded away. The remnants of this upper-crustal apron could now simply be submerged and out of view on the flanks of the dome offshore. This is yet to be shown, and for now the high pressure metamorphic rocks of the 'series' serve as the upper-plate of this Aegean metamorphic core complex.

CONCLUSIONS

The following conclusions have been reached:

(1) The lower-plate ('basement') garnet–mica schists

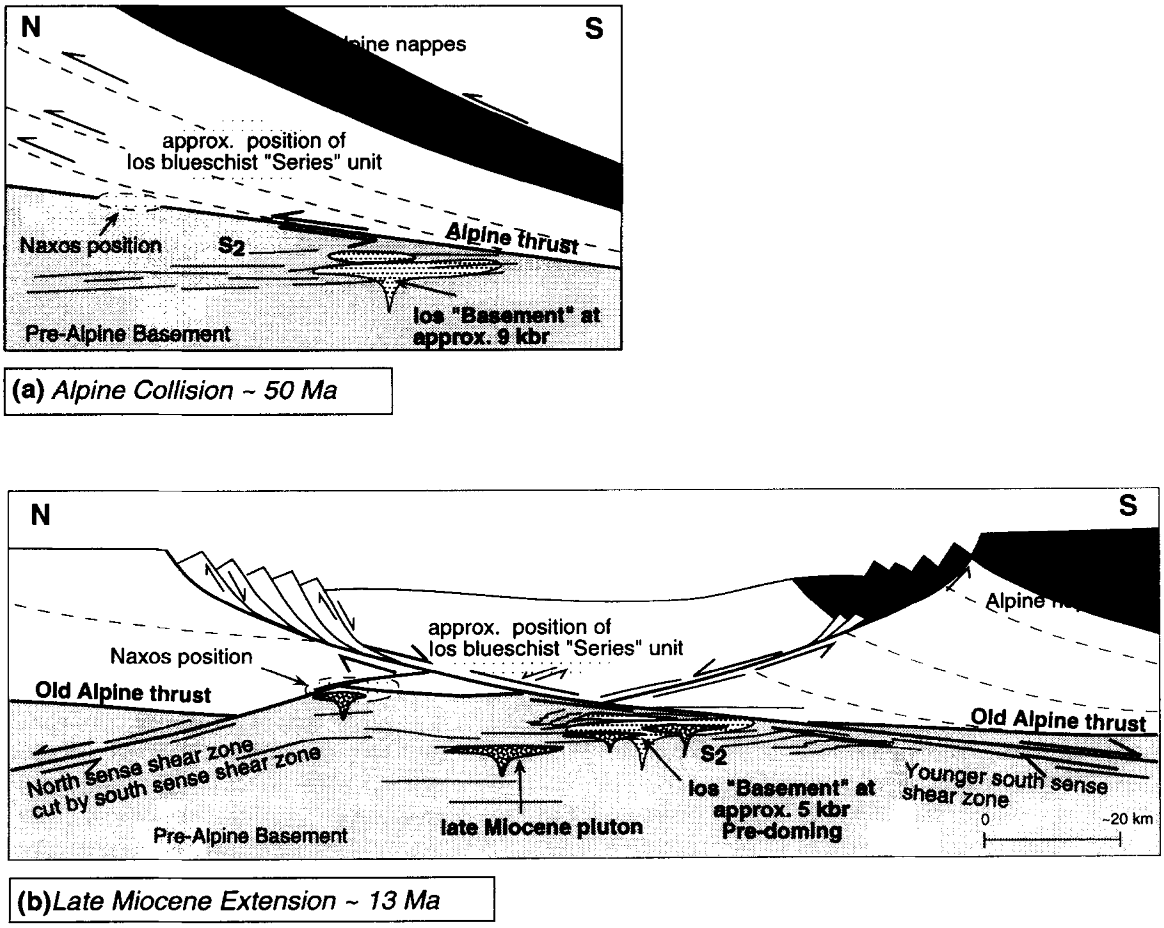

Fig. 12. (a) Schematic diagram showing the emplacement of the Cycladic blueschist (Alpine) nappe over Hercynian 'basement' rocks during the Alpine collision approximately 50 Ma. Note the approximate positions of the Ios 'series' and 'basement' units at that time. (b) Proposed geodynamic setting for the Miocene shear zones and plutonism found on Ios (pre-doming) and Naxos. By this time the Blueschist Nappe was already at mid-crustal levels. The South Cyclades shear zone cuts the north sense Naxos shear zone, thereby juxtaposing 'series' rocks with northward shear sense upon 'basement' rocks with southward shear sense.

record an Hercynian amphibolite facies metamorphism (M_0).

(2) M_1 Alpine high pressure–low temperature metamorphism resulted in the formation of glaucophane, chloritoid, and jadeite (preserved only as rare inclusions).

(3) Metamorphic parageneses in the 'basement' are dominated by the effect of the Miocene greenschist overprint (M_2).

(4) Five generations of penetrative ductile structures (D_1–D_5) have been recognized in the Ios 'basement'. The dominant fabric (S_2) is a gneissosity or a strongly differentiated schistosity. Granitoids were deformed during D_2 to produce a penetrative S_2 augen gneissic (mylonitic) foliation.

(5) Abundant overprinting evidence indicates two major deformations subsequent to the formation of S_2. D_3 was of sufficient intensity to produce recumbent folds and locally penetrative axial planar cleavage (S_3). Foliated granitoids with S_2 fabric were (locally) further deformed during D_4 to produce spectacular zones of *S–C* mylonites with north–south oriented L_4 mineral stretching lineations. S_2 is generally subparallel to S_4 (in D_4 shear zones) except where it has been thrown into (1–100 m scale) recumbent folds with S_3 axial plane.

(6) The 'basement' and the 'series' were juxtaposed by a top-to-the-south D_4 crustal-scale ductile shear zone (found in the uppermost structural levels of the 'basement'), and by gently dipping normal faults. This shear zone is the South Cyclades shear zone of Lister *et al.* (1984). It is Miocene in age and transposes all previous generations of structures.

(7) The geomorphology of the island is dominated by the effects of a N–S to NNW–SSE elongate structural doming of the S_2, S_3 and S_4 fabrics during D_5. In the north of the island the basement-series normal fault contact (a possible detachment fault), and the South Cyclades shear zone have been rotated into an apparent thrust sense by D_5 doming.

(8) The present lineation pattern on Ios is not entirely due to Eocene subduction or collision as suggested by earlier workers (e.g. Blake *et al.* 1981). On Ios we can demonstrate that significant reorientation of older lineations has taken place during D_4 Miocene stretching of the Aegean continental crust.

(9) Rocks from the overlying 'series' unit, unlike those on Naxos, are dominated by southward shear sense. There is also a regional dichotomy of broadly synchronous shearing senses (top-to-the north or south) for which there are three alternative scenarios: (i) bivergent regional extension; (ii) asymmetric extension of the

region dominated by one sense of shear and accompanied by minor antithetic shearing; and (iii) a period of deformation, dominated by one sense of shear, is closely proceeded by a period in which the other sense of shear is dominant. We suggest that the south directed South Cyclades shear zone followed local north directed shearing. We also suggest that local north directed shearing in the Ios 'series' rocks may be related to the north directed shear zones that controlled the evolution of the Aegean region to the north.

(10) The Ios metamorphic core complex is defined by a lower-plate (originally buried during the Alpine Eocene collision event) which has been intruded and deformed during a Miocene thermal pulse/plutonic event. During the Miocene thermal pulse the lower-plate 'basement' was tectonically denuded and exposed beneath the blueschist 'series' unit. The Ios core complex thus reflects an intrinsic relationship between early thrusting and later extensional tectonism; it is defined by basement rocks exhumed from beneath the high pressure nappes that originally overrode them.

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