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Basin development and uplift at an oblique-slip convergent margin: Nias Island, Indonesia

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Abstract: The structural geology of Nias is described in this paper via a transect across the strike of the island. Three sub-basins and a basement high are identified and the structure at depth is explored. The results show that the Nias area was subject to Oligocene and Early Miocene extension with the development of half grabens dropping down to the south-west.

The basinal successions were subject to two distinct phases of uplift and deformation; western areas were inverted during the Early Miocene whilst the whole of the island was subject to Pliocene tectonism.

The structural interpretation for the geology of Nias is supported by the stratigraphic record. The evidence presented in this paper suggests that the geology of the island is best explained by forearc extension and subsequent inversion rather than by the primary accretionary model.

INTRODUCTION

The understanding of convergent margin processes is crucial to an understanding of the geological evolution of regions such as Southeast Asia. The Sumatran Forearc in Western Indonesia offers a unique opportunity to study the Cenozoic to Recent evolution of an active convergent margin; islands with excellent exposures are located both within the present-day forearc basin and along its outer-edge (Fig. 1). The outer-arc islands, such as Nias Island, have most commonly been regarded as forming part of the accretionary complex that is currently active to the south-west of the outer-arc ridge (Moore and Karig, 1980). Islands such as those of the Banyak Group, within the present-day forearc basin, were however relatively poorly known prior to this study.

The geology of the Sumatran Forearc has been the subject of a recent multidisciplinary study by geologists from the University of London. The work has been concentrated on field based studies although geophysical studies (e.g. Milsom this volume) have provided additional control on both the onshore and offshore geology. The primary purpose of this paper is to outline a new structural interpretation for Nias Island. Detailed maps, structural data and cross-sections over Nias are presented and conclusions are drawn. In particular we show that islands such as Nias should not be considered as comprising part of an accretionary complex even though accretionary processes have been important in controlling the patterns of relative uplift and subsidence at the outer-edge of the forearc.

OUTLINE OF SEDIMENTARY HISTORY

A new stratigraphy for the Sumatran Forearc has been determined and is briefly outlined below. Temporal and geographical changes in sedimentation can be related to a number of key structural events which are summarised on Figure 2. Comprehensive details of the stratigraphy and the structural controls on sedimentation are presented in Samuel (1994).

Basement, where directly exposed on Nias, consists of an intersheared assemblage of rocks which are all of ophiolitic affinity (Figs. 2 and 3). Similar exposures occur extensively on Simeulue Island (Situmorang *et al.*, 1987) and on Bangkaru Island (Banyak Island Group), to the north of Nias. Furthermore deformed sections of ophiolitic material have been discovered on islands to the south-east of Nias (Batu Island Group; Samuel, 1994). Mélanges also occur on these islands and some of these mélanges contain blocks of ophiolitic material. These mélanges do not themselves form basement as they include and intrude blocks and sections of Neogene to Recent material (Samuel *et al.*, in press). The youngest age obtained for components of the ophiolite complex has come from a pelagic red chert which contains Middle Eocene radiolaria. The basement must therefore have been emplaced subsequent to this time but prior to the Mid-Oligocene when sediments were unconformably deposited above it (Fig. 2).

The initial sedimentation, as seen in the Oligocene sediments of the forearc islands, was deep marine with deposition at depths probably below the CCD (Moore *et al.*, 1980). Deposition continued conformably through the Late Oligocene into the Early Miocene and in some areas considerable thicknesses (over 6 km) of predominantly siliciclastic sediments were deposited. Shallow marine carbonate-dominated deposition occurred during the earliest Miocene in some areas adjacent to continued deep marine deposition (Fig. 2). Detailed study of the Lower Miocene successions on Nias has indicated that active extensional faulting was responsible for these stratigraphic variations (Fig. 2 and Samuel *et al.*, in press). In western parts of Nias a period of uplift and erosion is recorded during the Early Miocene (Fig. 2). This can be attributed to localised contractional reactivation of originally extensional faults (Samuel *et al.*, in press).

Regional subsidence commenced during the Mid-Miocene and continued through the Late Miocene whilst the most pronounced phase of

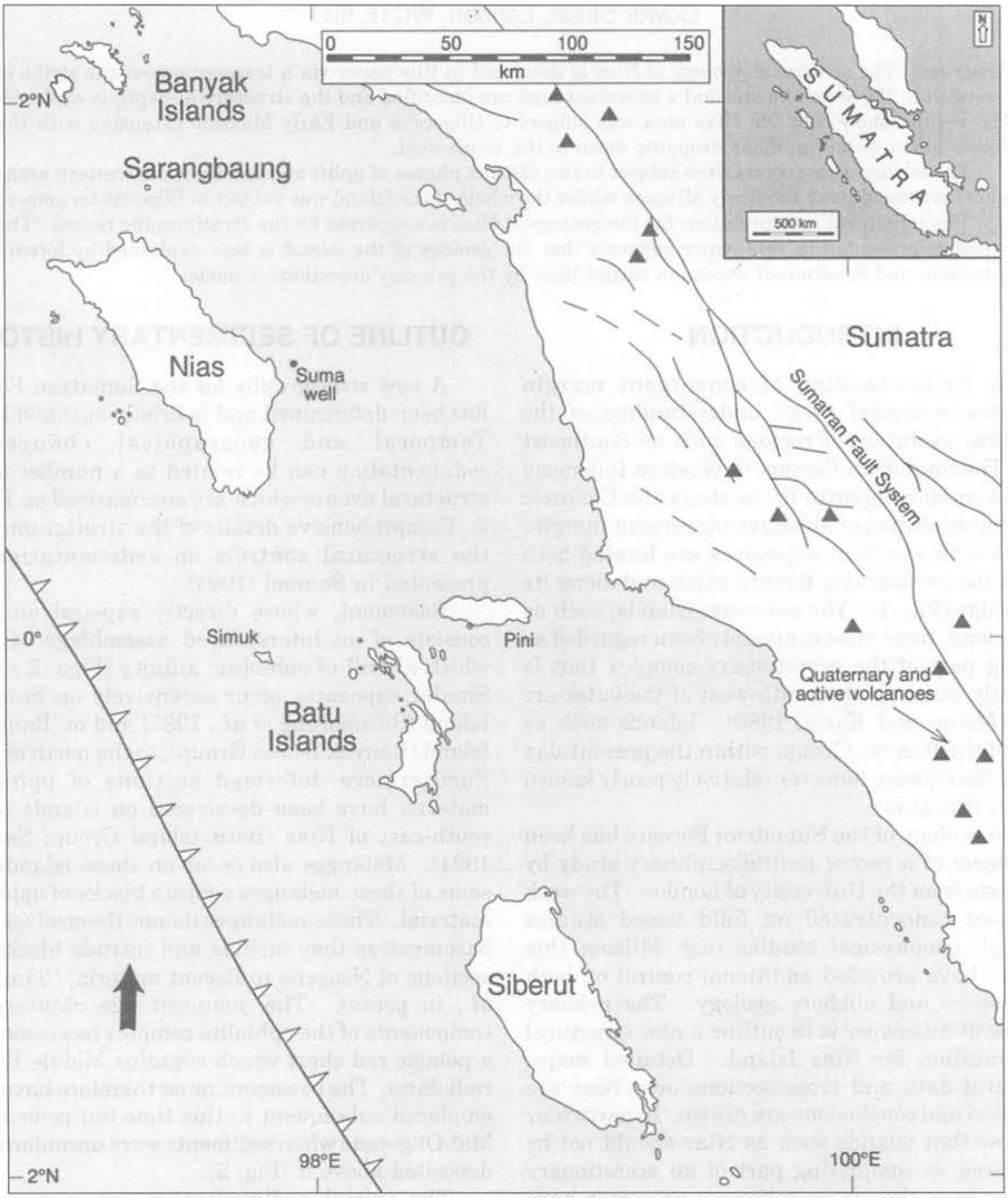
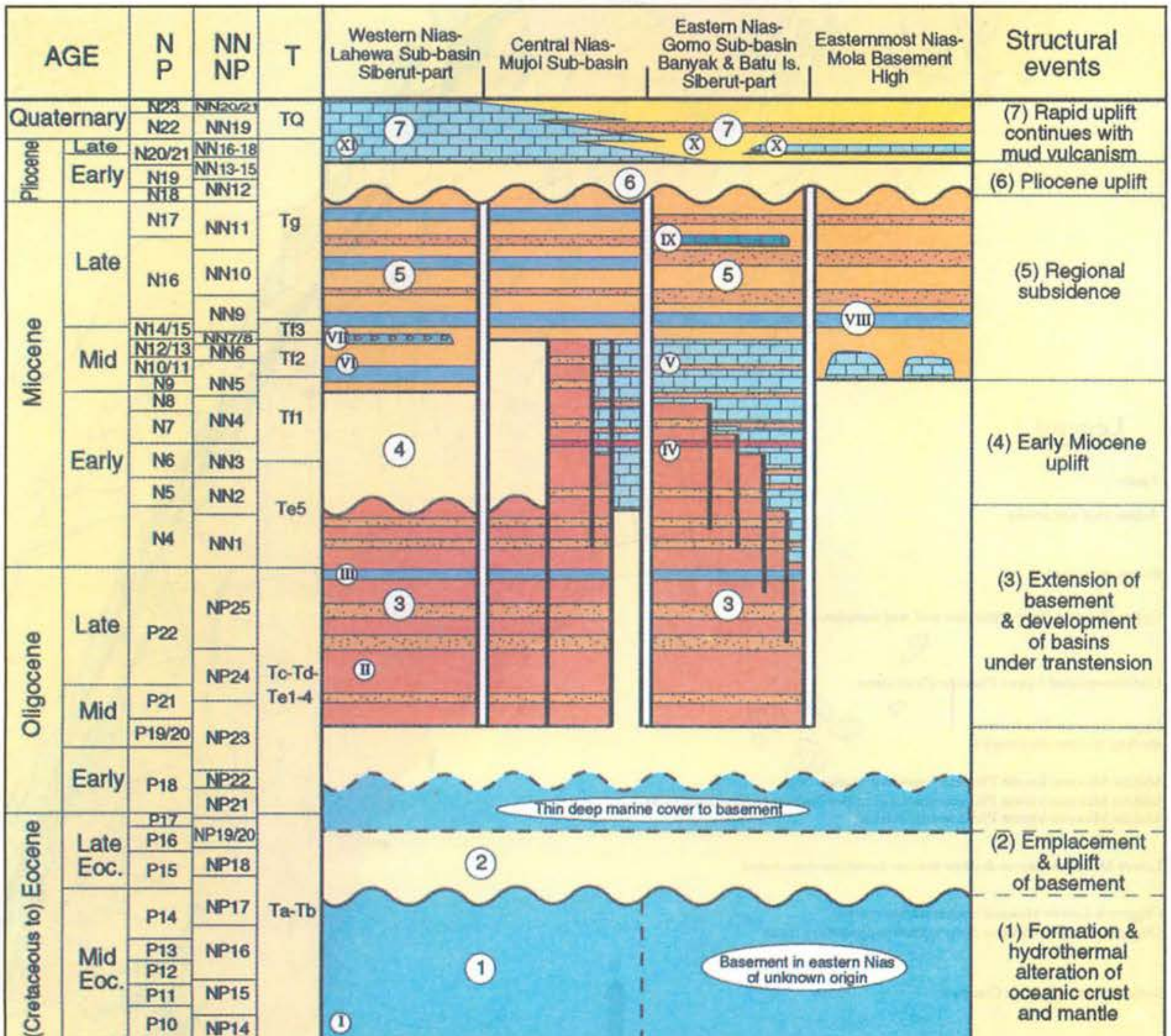


Figure 1. Location map showing the relative positions of Western Sumatra and the forearc islands of Nias, the Banyak Group, Sarangbaung, the Batu Group and Siberut. It is of note that whilst most of the islands lie along the line of the outer arc ridge, both Pini and the Banyak Group rest within the present day forearc basin.

deformation, which began in the Pliocene, continues up to the present day.

STRUCTURE ACROSS NIAS ISLAND

As part of our geological studies of the Sumatran Forearc a mapping programme was carried out over all areas of Nias. The geological map of Figure 3 was produced from a combination of field traverse data, SAR (Synthetic Aperture Radar) and LANDSAT images and aerial photographs. The mapping has revealed that there are important variations in structure along the strike of Nias. Despite this it has been possible however to identify three main sub-basins which trend along the strike of the island; we have called these, from northeast to southwest, the Gomo, Mujoi and Lahewa sub-basins (Fig. 4). In addition a basement high, the Mola Basement High occurs in easternmost Nias (Fig. 4). In order to give a representative view of the structure of the island we have chosen a line of section that cuts across the basement high and each of the sub-basins. The structural geology that is apparent along this line is described below from the northeast to the southwest and in the subsequent section of this paper these results are combined to produce an interpretative cross-section for Nias. Further details of the full range of



I = Ophiolitic basement, II = Oligocene-Lower Miocene deep marine sedimentary rocks, III = Tuffs, IV = Oligocene-Lower Miocene conglomerate marker, V = Lower-Middle Miocene shallow marine limestone-dominated sediments, VI = Middle Miocene-lowest Pliocene shelfal to upper bathyal sedimentary rocks, VII = diatomites, VIII = Middle Miocene-lowest Pliocene tuff marker, IX = Middle Miocene-lowest Pliocene limestone marker, X = Upper Pliocene-Pleistocene shallow marine siliciclastics, XI = Upper Pliocene-Pleistocene elevated reef complexes.

Figure 2. New chronostratigraphy for the Sumatran Forearc. The scheme is founded on detailed stratigraphic and biostratigraphic studies on all parts of Nias and the Banyak Islands; over 350 samples have been dated. The scheme is also readily applicable to the Batu Island Group, Sarangbaung and Siberut. In this diagram 'N' and 'P' denote planktic foraminiferal zones, 'NN' and 'NP' denote nannofossil zones and 'T' denotes far eastern letter stages.

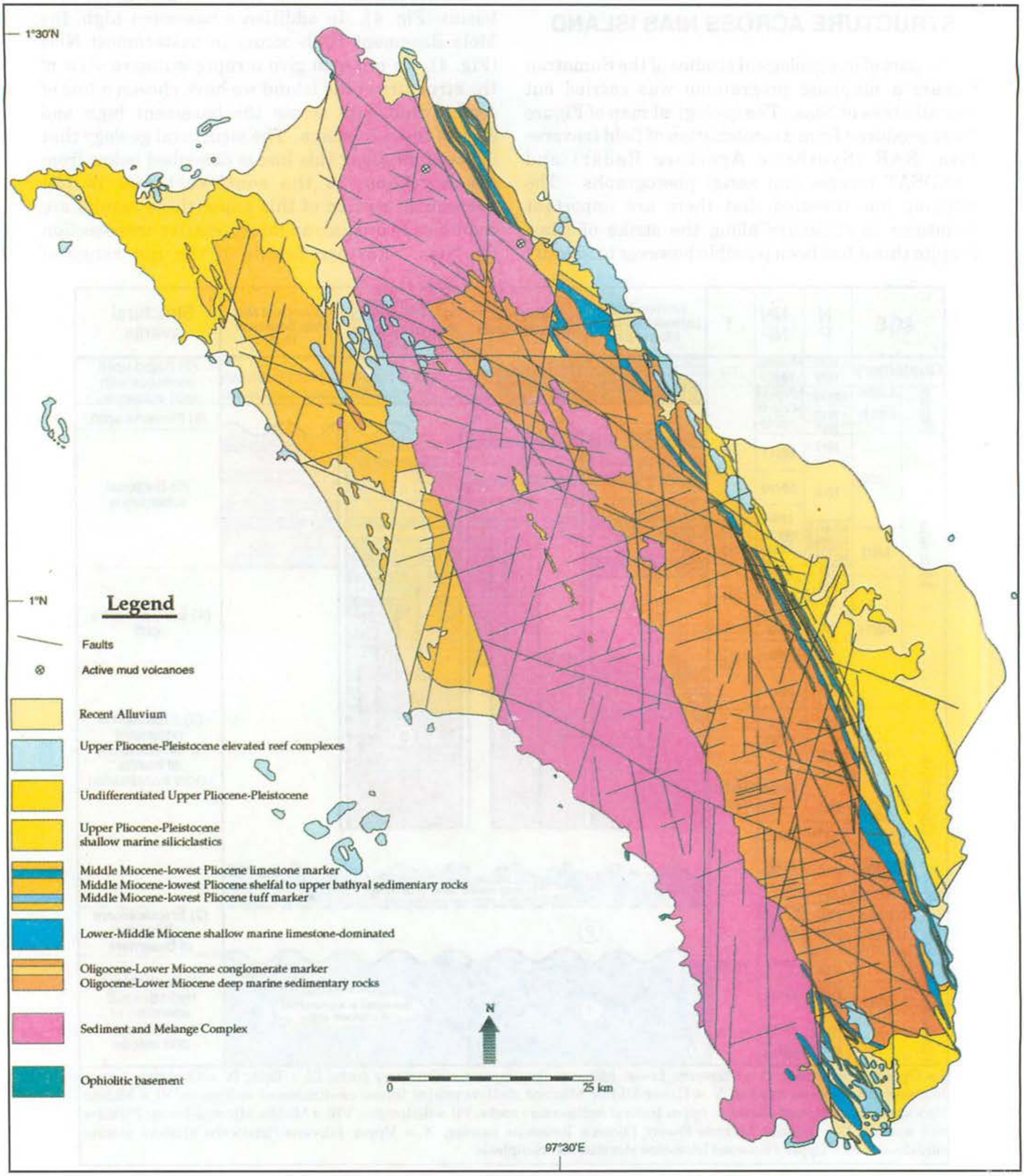


Figure 3. Geological map of Nias. The map has been constructed from field traverse data with further control from SAR (synthetic aperture radar), LANDSAT and aerial photographs.

structural variations on Nias are described and discussed in Samuel (1994).

EASTERNMOST NIAS-MOLA BASEMENT HIGH

The eastern coast of Nias extends to the south of Gunungsitoli around a prominent 'bulge' (Fig. 4). This 'bulge' is characterised by low relief and is largely covered by recent alluvium (Fig. 3). Weakly defined ridges can be seen however on SAR, LANDSAT and aerial photographs; in some areas these ridges are cut by rivers and it is apparent that they comprise the Upper Pliocene to Pleistocene (Fig. 3). Bedding dips are gentle to the northeast with values of 6–8° recorded in the Gawo river (Fig. 5).

Seismic lines were shot across easternmost Nias for Union Oil in the late sixties and although of low

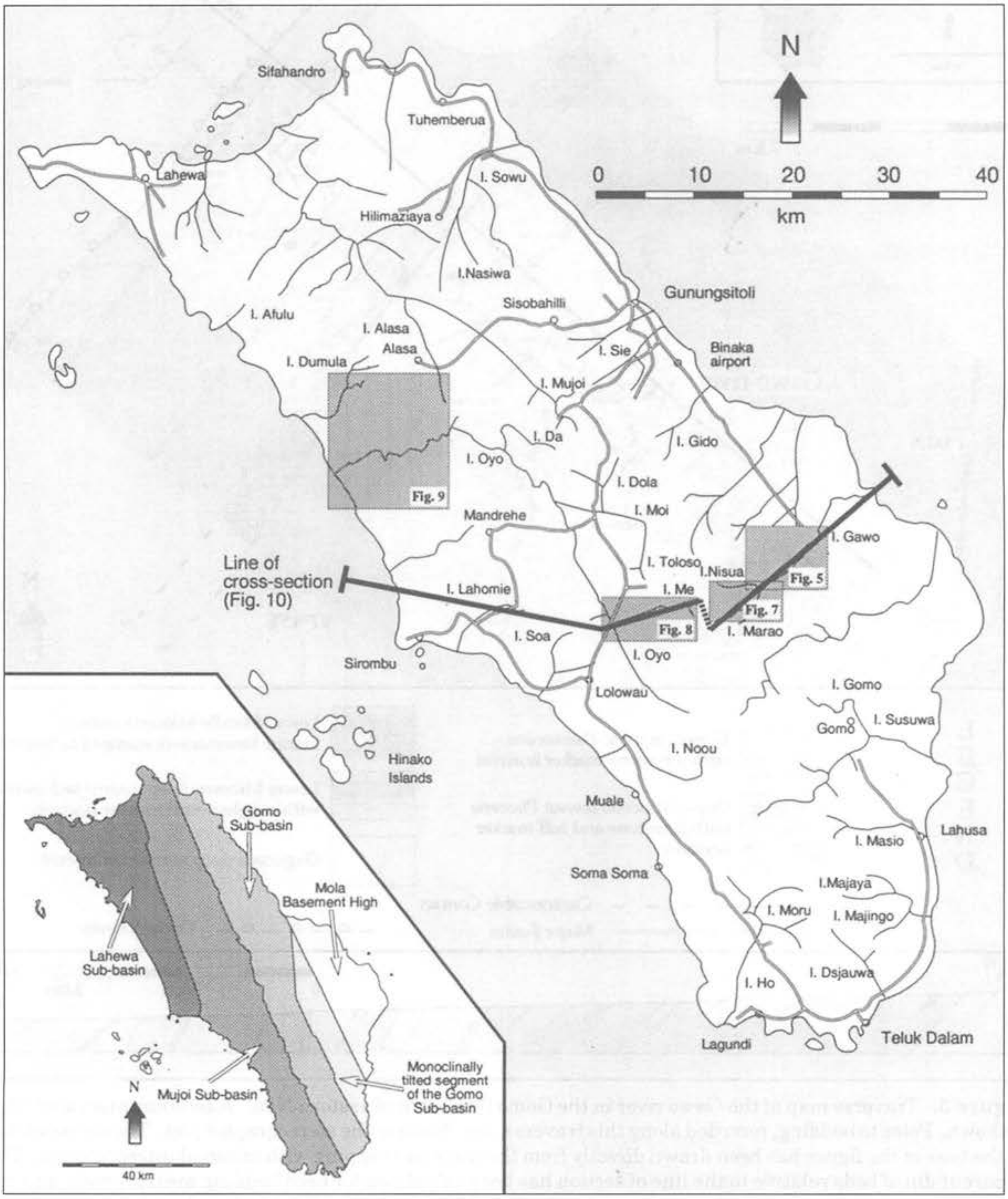


Figure 4. Location map for Nias island. The line across Nias, which is examined in detail in this paper, is shown as are the areas for which detailed geological maps are presented. The inset map shows the position of the Lahewa, Mujoi and Gomo Sub-basins, the monoclinally tilted segment and the Mola Basement High. The line of cross-section of Figure 10 has been chosen to cover all of these features.

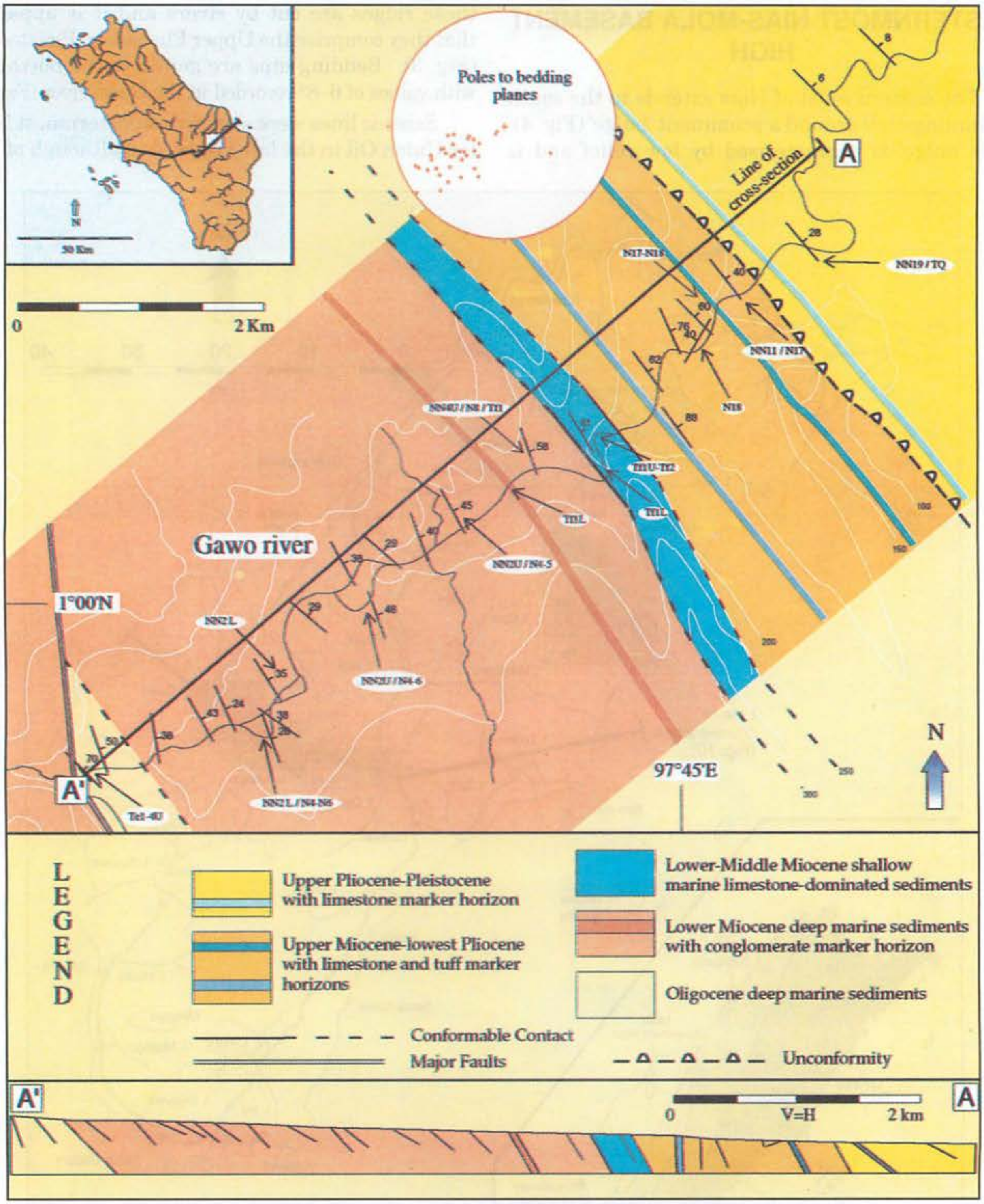


Figure 5. Traverse map of the Gawo river in the Gomo Sub-basin of eastern Nias. A contour interval of 50 m is shown. Poles to bedding, recorded along this traverse, are shown in the stereographic plot. The cross-section at the base of the figure has been drawn directly from the traverse mapping with minimal interpretation. The apparent dip of beds relative to the line of section has been calculated for each bedding measurement and the beds are shown simply as straight lines. The location of the Gawo river is indicated on the inset map as is the line of the final interpretative cross-section presented in Figure 10.

quality these lines reveal that basement lies at shallows depths in this region of Nias (Fig. 6). Gravity data further indicate the presence of a basement high in easternmost Nias; in particular large residual Bouguer gravity anomalies have been mapped in this area by Milsom (1993). *In situ* exposures of basement to the west of the Mola Basement High are ophiolitic; however, the nature of the basement beneath the forearc basin is uncertain (Karig *et al.*, 1979). Large gravity variations are recorded along the strike of the forearc (Kieckhefer *et al.*, 1981; Milsom *et al.*, 1990 and Milsom , 1993) indicating that the basement is most unlikely to be heterogeneous in nature.

High amplitude reflections are apparent on many of the seismic lines directly above basement. These reflections are indicative of the presence of carbonate buildups and the sediments at this level are tied to Middle Miocene carbonates recovered from the Suma Well (Karig *et al.*, 1979). The overlying Upper Miocene succession, which is readily apparent on seismic, can be tied directly to field outcrops as can the Pliocene unconformity and the overlying Upper Pliocene and Pleistocene sediments (Figs. 5 and 6). The Miocene succession clearly thickens to the southwest (Fig. 6) whilst north-easterly prograding clinoforms are evident in the Upper Pliocene/Pleistocene.

EASTERN NIAS AND THE MONOCLINAL FLEXURE — GOMO SUB-BASIN

A steepening of the Miocene strata can be seen in the most southwestern parts of the seismic lines shot across easternmost Nias (Fig. 6). Unfortunately no attempt has ever been made to acquire seismic further to the south-west due to the considerable relief of the Middle and Lower Miocene ridges that run along that part of the island. The monoclinal steepening is readily apparent in the field. Dips in the Gawo river increase from 8° in the Pleistocene to sub-vertical in the Middle Miocene where the river cuts through a ridge largely composed of limestones (Fig. 5). This steepening has been termed a flexure by past workers (Moore and Karig, 1980). This flexure is a major feature that can be traced along much of eastern Nias. Whilst the sediments show a general monoclinal steepening, gentle folding and more rarely small-scale thrusting, are apparent within the Middle Miocene limestones and within the Upper Miocene section in the Gawo river (Fig. 5). Furthermore similar structures are evident along the line of the flexure both to the southwest and the northeast.

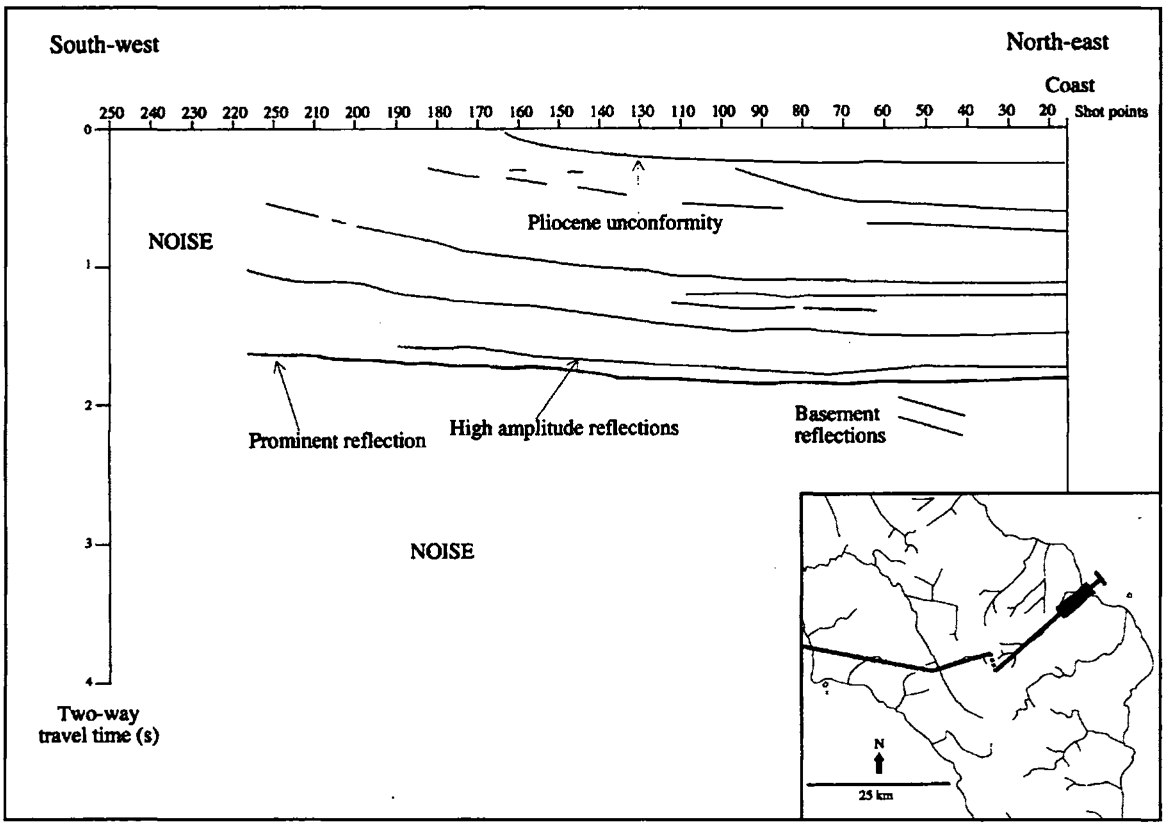


Figure 6. Line drawing of seismic data shot over the Mola Basement High. Vertical exaggeration is approximately x2 and the line is unmigrated. The line is tied to an offshore line which crosses the Suma Well (Fig. 1). The location of the onshore seismic is indicated on the inset map as is the line of the cross-section presented in Figure 10.

A stratigraphic thickness of over 3 km of Lower Miocene to Upper Oligocene deep marine sediments are exposed immediately to the south-west of the flexure (Fig. 5). These sediments all dip to the northeast; dips vary between 24° and 58° without any consistent trend. The uniform nature of the structure is clearly visible on SAR and LANDSAT images and on aerial photographs. Individual ridges can be traced for over 20 km along strike. Dating of a number of samples indicates that there are no 'hidden' structural repetitions of the section; the sedimentary rocks becomes progressively older to the southwest (Fig. 5). Apart from syn-sedimentary slides and slumps deformation is limited to small-scale normal faulting. Two populations of normal faults have been recognised and their structural significance is discussed below.

A considerable area of the Gomo Sub-basin is therefore characterised by a near uniform northeast bedding dip with only minor and localised indications of compressional deformation at the present erosion level. This monoclinally tilted segment is bounded by faults (Fig. 4) and greater degrees of deformation occur to the northwest and southwest of this segment.

SAR, LANDSAT and aerial photographic images reveal a pronounced change in the morphology of the ground to the southwest of the monoclinally tilted segment. This change coincides exactly with an abrupt transformation in structural style as recorded in the Marao and Nisua rivers, immediately upstream of their confluence with the Gawo river (Fig. 7). Unfortunately there are no exposures in the vicinity of the confluence. Contractional deformation with northeast vergence is however revealed along the lower reaches of the Nisua river with gentle dips on southwest limbs and steep to overturned (southwest dipping) dips on the northeast limbs of the folds (Fig. 7). Fold closures are only rarely exposed and are frequently complicated by contractional faulting although offsets on the faults are small (generally less than 1 m). Fold plunge measurements in the field of sub-horizontal to the northwest are consistent with the fold trend revealed by a stereographic plot of poles to bedding (Fig. 8). Exposures along-strike in the downstream parts of the Marao river are less common. In one atypical exposure however thin bedded turbidites are deformed by northeast dipping reverse faults and tight folds. The south-westerly vergence is opposite to that recorded along-strike in the Nisua river. The outcrop is of further interest as the contractional structures crosscut small-scale extensional faults. These faults are calcite veined and must pre-date the phase of contractional deformation described above, in contrast to many other normal faults on Nias which post-date the Pliocene unconformity. Two phases of normal faulting are therefore indicated.

Upstream in both the Marao and Nisua rivers a marked change in strike is measured (Fig. 7). Beds dip to the north and folding is absent. Further atypical (i.e. not parallel to the strike of the island) bedding attitudes are observed, from aerial photographic studies to occur, along-strike, over much of eastern Nias and they cannot be mapped as very large folds. The atypical strikes are particularly apparent to the south-west and are recorded in field traverses; 35 km to the southwest of the Marao river, in the middle and upper reaches of the Majingo river where the predominant strike of the Lower Miocene sedimentary rocks is northerly.

CENTRAL NIAS-MUJOI SUB-BASIN

The Mujoi Sub-basin is separated from the Gomo Sub-basin by a major southeast striking fault that can be traced the length of Nias Island (Figs. 3 and 4). The fault is exceptionally well defined in the southern central half of the island where it separates two regions of markedly different geology; to the northeast folded and rotated Lower Miocene sedimentary rocks are exposed (see above); to the southwest a large area characterised by deformed sedimentary sections and mélanges ('sediment and mélange complex') occurs (Fig. 8). This sharp transition is reflected in a marked change in ground morphology best observed on SAR images and in a change in soil and vegetation types which is emphasised on LANDSAT images. The contact can be traced on SAR and aerial photographs and mapped in detail (Fig. 8). Such an exercise reveals that the lineament is uncharacteristically sinuous. The plane of this fault is clearly not as steep as those of many of the other major faults on Nias; the relationship of the contact with topography implies a moderate (~30°) dip of the fault to the southwest. The fault intersects the Me river in two places and in both cases, whilst the actual contact is not directly exposed, deformed Lower Miocene sedimentary rocks of the footwall are juxtaposed against sediment and mélange complex in the hangingwall (Fig. 8). In the downstream locality mudstones and thin bedded turbidites are poorly exposed. The mudrocks are heavily sheared, brecciated and calcite-veined and the sandstones exhibit pressure solution seams. A predominant shear fabric to the south-west is measured through the extensive section (exposed, albeit poorly, over 25 m). In the second locality a widespread zone of fold and thrust/reverse fault deformation is apparent in the turbiditic succession. Both these outcrops yield the same northeasterly vergence which is consistent

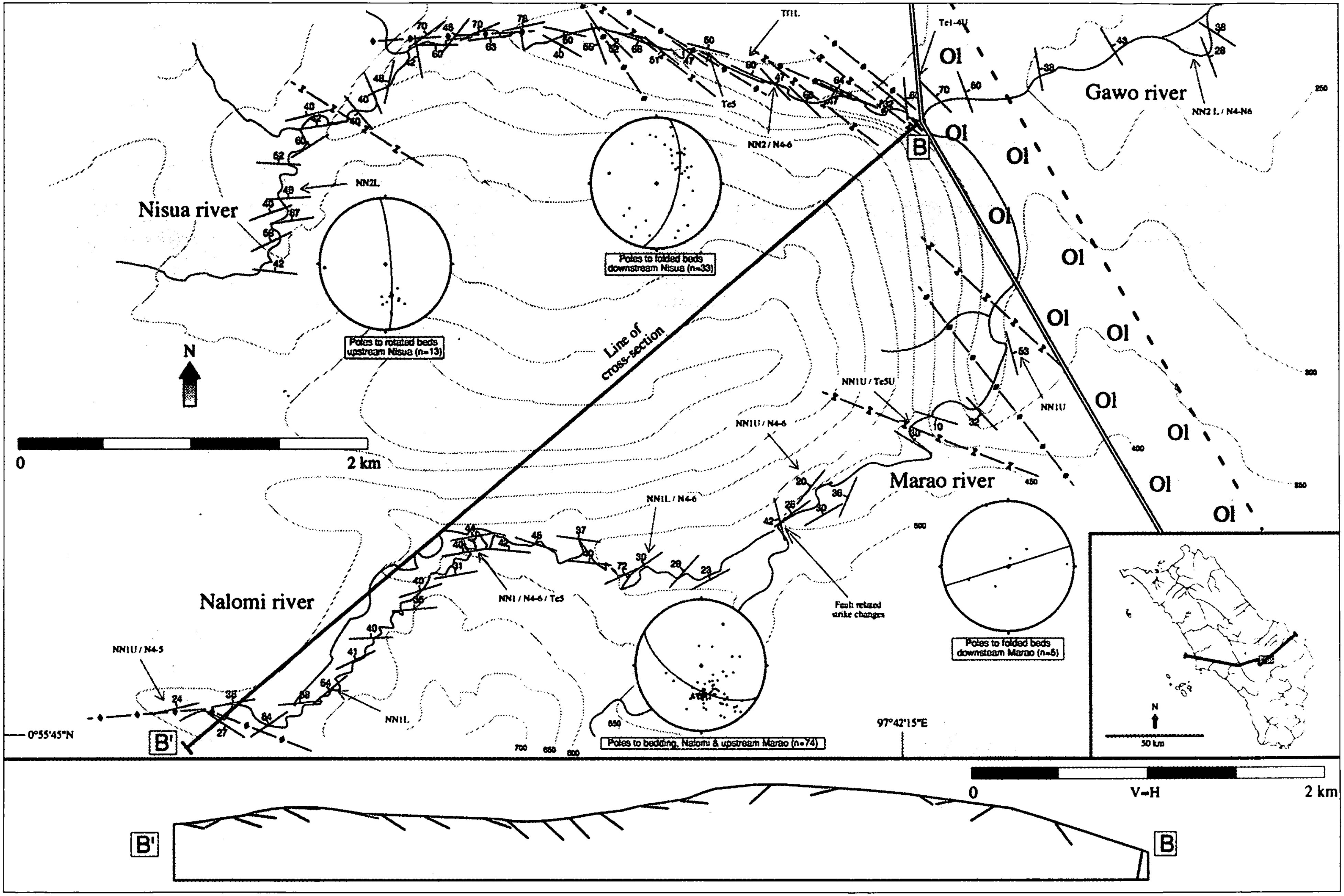


Figure 7. Traverse map of rivers in the Gomo Sub-basin, eastern Nias, to the south-west of the Gawo river. All rocks are of deep marine facies and are of Early Miocene age except where indicated as Oligocene (Ol) in the uppermost reaches of the Gawo river. A contour interval of 50 m is shown. Poles to bedding for separate sections of the rivers are plotted on the stereographic plots. The cross-section is a summary of the traverse data recorded in the Marao and Nalomi rivers. These data have subsequently been incorporated into the cross-section across the whole of Nias (Fig. 10). Mapping of along-strike areas of Nias, as above, reveals that deformational styles vary along the strike of the island. The location of this part of Nias, relative to the rest of the island, is indicated on the inset map as is the line of the cross-section presented in Figure 10.

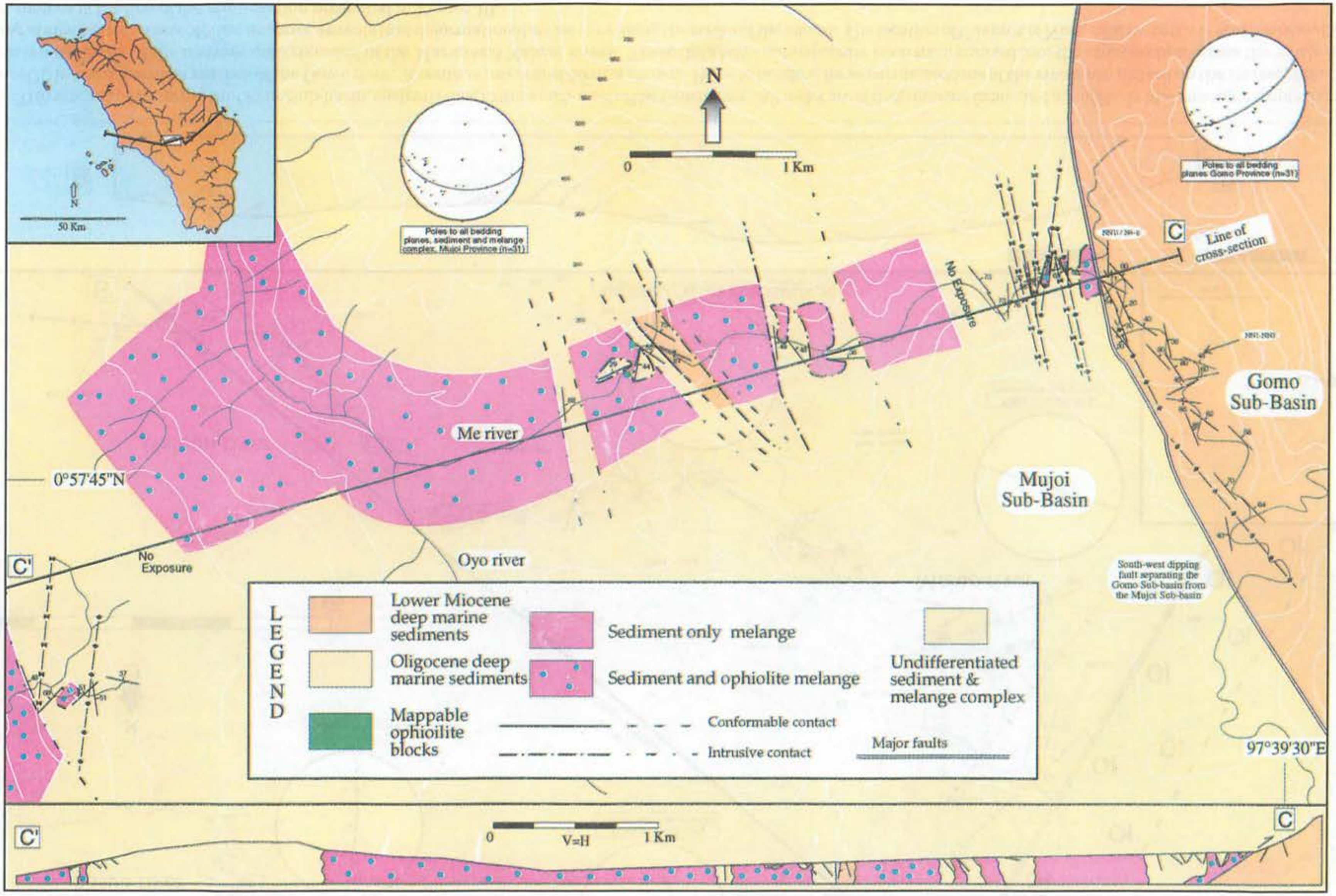


Figure 8. Traverse map of a selected part of the Mujoi Sub-basin, central Nias, with part of the Gomo Sub-basin to the northeast. A contour interval of 50 m is shown and poles to beds recorded during the traverse are plotted on the stereographic plots. Numerous mélanges are exposed within the Mujoi Sub-basin at the present-day erosion level. Two main groups of mélange have been differentiated and mapped: 'sediment-only mélanges' containing inclusions of sedimentary (non-ophiolitic) material and 'sediment and ophiolite' mélanges containing, in addition, ophiolitic inclusions. It is important to emphasise that the contacts of these mélanges with the sedimentary sections into which they intrude have by necessity been simplified and in cases drawn as straight lines so that the map can at least provide a graphical representation of the relative distribution of deformed sections and mélanges. In practice it proves impossible to extrapolate contacts any significant distance away from the river/road cuts in which they are exposed and it is not possible therefore to map the unexposed areas between traverses with any confidence. It is for this reason that the sediment and mélange complexes have been mapped as a single unit on the large scale geological map (Fig 3). Similarly the mélange contacts are drawn as sub-vertical on the summary cross-section although in reality the contacts are extremely complex in three dimensions.

Table 1. Summary of key points concerning the mélanges on Nias.

Distribution	Extensive development in Mujoi Sub-basin, parts of Lahewa and Gomo Sub-basins.
Inclusions	At least 50% and commonly 90% Oligocene and Lower Miocene sedimentary material. Other components recorded in some but not all of the mélanges include basement clasts and Middle Miocene to Pleistocene sediments.
Deformation of inclusions	Deformation styles of mélange blocks and clasts are the same as those recorded in the deformed sedimentary successions at the margins of the mélanges. Some sedimentary inclusions exhibit brecciation, pinch and swell and web structure (as seen also at the mélange margins).
Matrix	Mudrock. This mudrock has the same composition and thermal history as the Oligocene and Lower Miocene mudrocks. In some sections it contains microfossils which are identical to those in the sections into which the mélanges have intruded.
Deformation of matrix	Scaly foliation is pervasively developed throughout the mélanges. The fabric is generally sub-vertical, although in places it is folded and aligned parallel to the margins of the mélanges.
Mélange-deformed sedimentary section contacts	Contacts are always intrusive with the mélanges intruding sections from the Oligocene up to the youngest formations of the study area. Intrusions propagate along bedding planes and extensional fractures developed in the deformed sedimentary sections at the margins of the mélanges. The mélanges map out as irregular intrusions.
Timing of formation	The major, and probably sole, phase of mélange formation initiated during the Pliocene. Mélange formation is continuing to the present day in the form of mud volcanoes.

with a south-westerly dip on the fault and suggests that the latest stage of movement on the fault was contractional.

The south-western edge of the Mujoi Sub-basin is bound by a further south-east striking fault. The fault is obscured in one area by a Holocene elevated reef complex (Fig. 3) and it appears that movements along the fault did not occur after the reefs were deposited. The fault, whilst locally offset (as with the other major southeast striking faults), appears to cut straight through topography implying a steep dip. It is important to note however that the relief in this region of Nias is mild in comparison to that in the central part of the island.

The deformed sections of the Mujoi Sub-basin show similar styles of deformation to that recorded in the Gomo Sub-basin to the west. The predominant vergence of the contractional structures is to the northeast although in some areas of the Mujoi Sub-basin the majority of the structures verge southwest (Moore and Karig, 1980; Samuel, 1994). In general the sedimentary fill exposed in the Mujoi Sub-basin is older than that of the Gomo Sub-basin. Not surprisingly vitrinite reflectance values for mudrocks are greater suggesting that the sediments were more deeply buried.

It has been recognised since the work of Moore and Karig (1980) that certain areas of Nias are characterised by 'belts' of mélange which separate areas of deformed sedimentary rocks (the 'sediment and mélange complexes' of this study). Moore and Karig (1980) suggested that these mélanges were tectonic in origin. Central to their accretionary prism model was the hypothesis that the mélanges had already formed prior to the Miocene and furthermore the idea that the mélanges actually formed basement to the sedimentary successions. Moore and Karig (1980) reported that they rarely discovered exposures that revealed any form of contact between the mélanges and the sedimentary successions. Contacts were however identified in many areas during this study and it is clear that these contacts are always intrusive. Our observations on the key features of the mélanges are summarised in Table 1. Further to this it is important to note that firstly: no asymmetry is evident in the nature of the contacts; there is no indication that the nature of 'western' contacts is any different from that of 'eastern' contacts; secondly: the mélanges do not map out as continuous belts along the strike of the island.

There is no doubt that the mélanges are diapiric in origin; they are composed predominantly of Oligocene and Lower Miocene sedimentary material but include and intrude *all* the younger formations on Nias. Whilst it appears that the scaly clay matrix to the mélanges may have been derived from overpressured basal Oligocene and Lower Miocene sedimentary successions the possibility cannot be ruled out that either the clay and/or the fluids may have originated from the basement, or indeed laterally or from below it. Therefore whilst the mélanges did not form within an accretionary complex, fluids derived from the accretionary prism may have promoted the diapirism. The field relations (Table 1) show that the major phase of diapiric activity occurred during Pliocene deformation; however, active mud volcanoes in northern Nias (Fig. 3) attest to continued diapiric activity.

WESTERN NIAS-LAHEWA SUB-BASIN

The Lahewa Sub-basin has been little studied by all previous workers on Nias with the exception of Hopper (1940) (The observations outlined below are consistent with those of Hopper). There are two main reasons why the area has been relatively neglected. Firstly, large areas of northern and western Nias are inaccessible except by foot and secondly the area is characterised by poor exposure. Relief is gentle and low lying areas are covered by recent alluvium. River systems are swampy and poorly incised, thereby affording only low levels of exposure.

Traverses across the sub-basin reveal the extensive presence of Middle Miocene to lowest Pliocene sedimentary rocks (Fig. 9) with a broad wavelength, northeast to southwest, folding pattern. The 'apparent' occurrence of mélange is extremely limited; mélange was only identified at one locality within the Lahewa Sub-basin during this study however Hopper (1940) reports "intrusions" at a number of localities and these intrusions appear to resemble the diapiric intrusions that are common to the east, in the Gomo, and particularly the Mujoi, Sub-basins. A second feature that Hopper (1940) reports, that is confirmed by this study, is the presence of a localised Lower Miocene unconformity (Fig. 2). The unconformity is apparent in the Maowa river (Fig. 9) of the Lahewa Sub-basin. It is of note that the unconformity has also been recorded, in some (particularly western parts) of the Mujoi Sub-basin during this study and by Hopper (1940); these areas lie to the northwest of the line of section concentrated on in this paper. It is apparent therefore that certain segments of the Lahewa and Mujoi Sub-basins were subject to uplift (and erosion) during the Lower Miocene at a time when conformable sedimentation was occurring over much of the island (Fig. 2). Further evidence for this localised and fault-controlled Early Miocene uplift comes from apatite fission track analyses (Samuel *et al.*, in press).

CROSS-SECTION THROUGH NIAS ISLAND

The cross-sections presented above can be combined to provide a transect across Nias with the interpretation of the geology of the island extended to greater depths. Whilst there are a number of possible interpretations for the structure at depth, the section below draws attention to factors which have influenced the construction of the cross-section which is shown in Figure 10.

A) Depth of basement and structure below the Mola Basement High

Flat lying basement of unknown lithologies is drawn at a depth of 2 km below the bulge of eastern Nias. This interpretation is drawn with confidence from the seismic data where basement is recorded at 2 seconds (two-way travel time). The presence of reefs lying directly on basement is indicated by the high amplitude reflections on the seismic lines. The general flat structure of the sediments and the presence of the Pliocene unconformity are indicated both by the field and seismic data.

B) Contact of the Mola Basement High with the Gomo Sub-basin

The interpretation of this contact, which corresponds to the flexure of Karig *et al.* (1979) is crucial to all interpretations of the geology of Nias. No seismic data have been recovered over the contact so all reasoning is based on field data. Traverses from rivers such as the Gawo illustrate that at least 5 km of section dip near uniformly to the northeast as part of a monoclinally tilted segment. These strata cannot continue indefinitely towards the Mola Basement High, and it is not possible to continue the basement below the Mola Basement High into the Gawo region at a depth of 2 km. Some form of relatively steep contact is required. A large fault has not been mapped at the surface by any workers; previous workers have recognised instead the 'flexural steepening' of the section in a southwesterly direction away from the Mola Basement High as shown on the cross-section. The structure at depth is most sensibly interpreted as a normal fault, with dip to southwest. The contractional structures recorded locally in the Gawo river and along-strike areas of the monoclinally tilted segment can consequently be explained in terms of minor compressional reactivation of this fault. This interpretation is different to that of Karig *et al.* (1979) although in both interpretations a major fault, steeply dipping to the southwest is indicated.

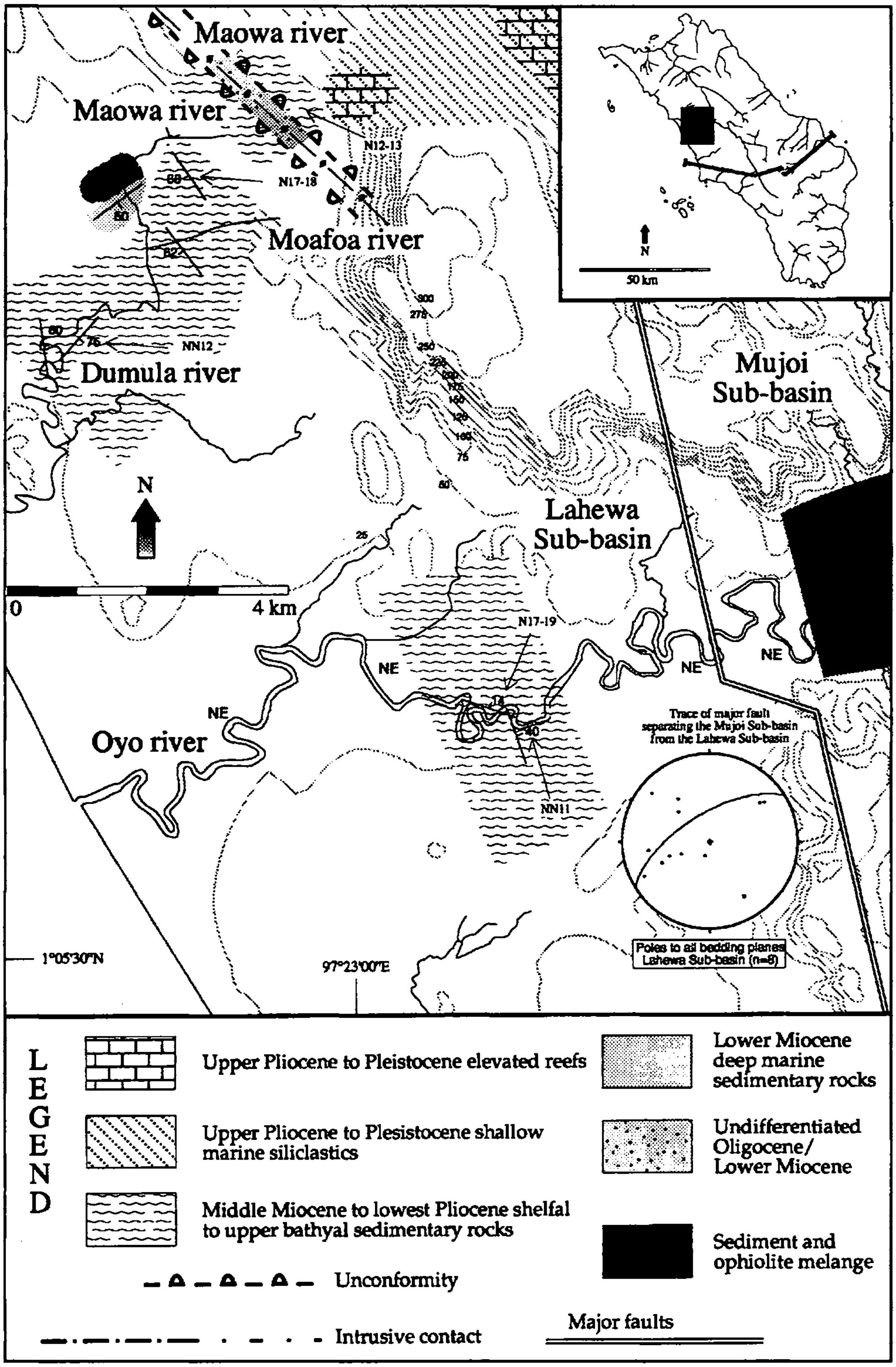


Figure 9. Map of traverses in western Nias across the Lahewa Sub-basin. Although the final line of cross-section shown in Figure 10 runs to the south of the area shown (see inset map), this part of the Lahewa Sub-basin is chosen to represent the geology. This is for two reasons; firstly, although not fantastically exposed the level of exposure is higher than in other areas of the Lahewa Sub-basin; secondly many other areas of the Lahewa Sub-basin are covered by recent alluvium or elevated Quaternary reefs (Fig. 10). The data recorded from this part of Nias have therefore been incorporated into the cross-section of the island. The contour interval shown in this map is 25 m as the relief is generally very gentle. As with the other maps a stereographic plot of poles to bedding for the area shown is included in the figure.

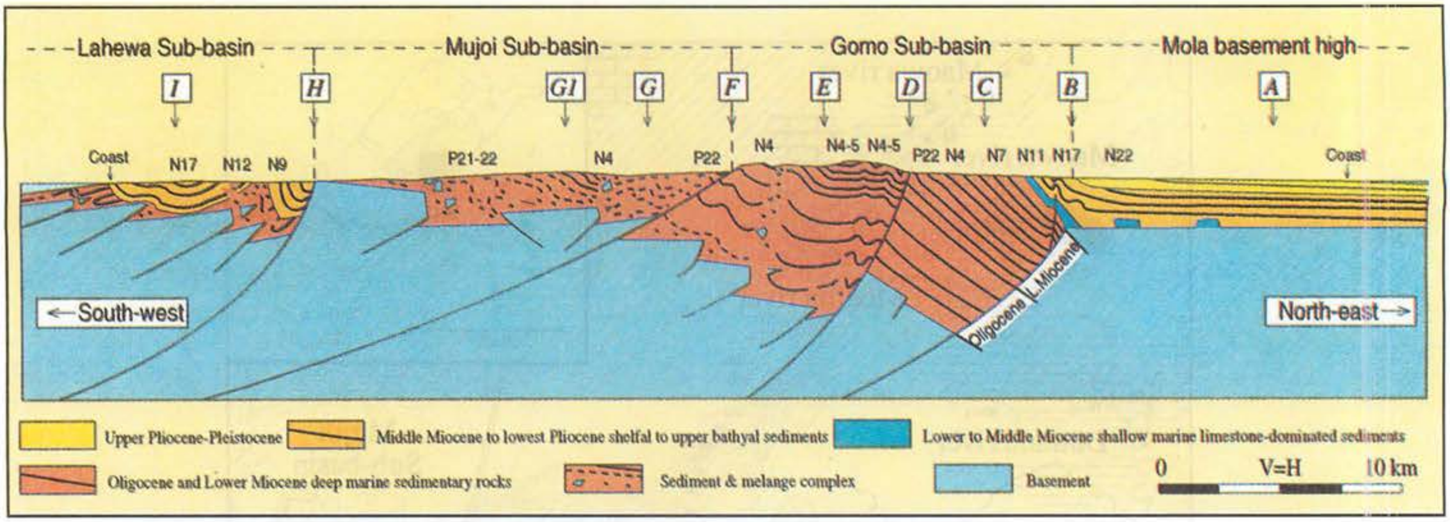


Figure 10. Cross-section through Nias Island. The section is based largely on the detailed observations which are summarised in Figures 5-9 and the line of section is shown on Figure 4. The section is interpretative at depth however detailed justification and discussion of the interpretations for each part of the island are presented in the text and are referred to by the letters *A* to *I*. Critical ages are shown using the planktic foraminiferal zonation scheme.

C) Structure of the monoclinally tilted segment

The simple monoclinal structure of the segment as revealed in the Gawo river and along-strike areas (in the field and on SAR, LANDSAT and aerial photographs) is drawn on the cross-section. The minor changes in dip recorded along the Gawo river section can be explained as a consequence of the common small-scale normal faulting.

The stratigraphically lowest part of the section exposed at the surface is dated as Late Oligocene (from the uppermost reaches of the Gawo river). It is known that deep marine sedimentary rocks of probable Mid-Oligocene age occur within the Gomo Sub-basin as they have been brought up in diapiric mélanges but it is not possible to directly measure the thickness of the Oligocene section. It is possible, however, to gain an estimate of the thickness of the Oligocene from a comparative consideration of the succession of Lower Miocene sedimentary rocks exposed in the Gawo river. In this river the thickness of 3.3 km spans a 9 Ma time interval. Assuming the Oligocene succession was deposited over an 8 Ma time interval (i.e. Mid-Oligocene to latest Oligocene) the thickness could be expected to be about 3 km. The Oligocene rocks are more compacted than those of the Lower Miocene and this factor would reduce the thickness estimate, however sedimentation rates during the Oligocene were probably more rapid than during the Lower Miocene as sea-level was at a low and sediment supply was correspondingly high. The figure of 3 km is therefore reasonable and is employed as a working thickness for the cross-section.

D) Contact of the monoclinally tilted segment with southwestern segments of the Gomo Sub-basin

The southwestern boundary of the monoclinally tilted segment is defined by a southeast striking fault and rocks to the southwest exhibit a marked change in structural style. Age dating reveals that sections immediately to the southwest are down-thrown relative to the monoclinally tilted segment. The straight trace of the fault implies a relatively steep dip. There is no direct evidence to suggest a southwesterly dip on the fault however the contact is drawn as such for two reasons. Firstly, contractional structures which may be related to reactivation of the fault have a predominant steep northeast vergence. Secondly, other major southeast striking faults on Nias dip to the southwest.

E) Structure of southwestern segments of the Gomo Sub-basin

The structure at the surface is drawn directly from field measurements. The cross-section cannot illustrate the off-strike rotation of individual segments demonstrated from field and remote sensing studies. The general dip of basement to the northeast reflects the overall down-section progression from the Gomo Sub-basin to the south-western boundary of the Mujoi Sub-basin where basement is directly exposed.

An intrusion of mélange is drawn schematically on the cross-section to represent the along-strike occurrence of mélange (Fig. 3). The mélange is illustrated in steep and complex contact with the sedimentary rocks it intrudes which is consistent with all field observations of the contacts of the mélanges. The mélange is shown as originating largely from the basal sedimentary successions as suggested by field, vitrinite, XRD and microfossil data. Basement material is shown in thrust contact with the lower part of the sedimentary succession at depth. This reflects direct observations made at the surface in the Dola river of the Mujoi Sub-basin (Samuel *et al.*, in press). Overthrust basement material is shown as being broken up and incorporated into the rising diapiric mélanges.

F) Contact of southwestern segments of the Gomo Sub-basin with the Mujoi Sub-basin

This contact is clearly defined on SAR and LANDSAT images and a moderate southwesterly dip is revealed from aerial photographic studies. Direct field observations indicate a structural (faulted) origin to the contact and the sections on the hanging-wall side of the fault are confidently identified as older than those of the footwall. In addition vitrinite reflectance values of samples from the hanging-wall are significantly greater than reflectance values from footwall samples. Basement is therefore drawn up-thrown on the hanging-wall.

G) Structure of the Mujoi Sub-basin

Field observations indicate that the area of the Mujoi Sub-basin crossed by the line of the cross-section is characterised by the occurrence of sediment and mélange complex. The pervasive and complex nature of the mélange intrusions cannot be fully represented at the scale of the cross-section. The cross-section does however accurately show some areas where large thicknesses of Oligocene and Lower Miocene strata are preserved as coherent sections (*G.1*). These sections are visible on the SAR image and can been mapped, through the sediment and mélange complex, at 1:100,000 scale. Such areas, consisting of deformed sedimentary rocks, usually stand proud of areas containing more mélanges as the matrix to the mélanges, although hard when fresh, weathers very rapidly.

The structure at depth is very largely schematic. Basement is shown dipping northeast as the surface geology records a down-section progression to the southwest with intact basement exposed to the southeast along-strike of the section (Fig. 3). Contractional faults are drawn offsetting the basement at depth in order to provide an explanation for the deformation revealed by the surface geology. These structures are depicted as steeply dipping, generally to the southwest, but with some dipping northeast, to account for local reverses of the vergence direction.

H) Contact of the Mujoi Sub-basin with the Lahewa Sub-basin

Lineament analyses and the work of Hopper (1940) again suggest this contact is steep although it does not cut through such great relief as some of the other contacts. It is drawn with a southwesterly dip for the same reasons as the contact described in *D*.

Rocks at the surface on the proposed hangingwall side of the fault are Middle-Upper Miocene in age and are therefore younger than the basement and the Oligocene and Lower Miocene rocks of the footwall.

I) Structure of the Lahewa Sub-basin

The structure of the westernmost sub-basin on Nias remains poorly constrained because of the poorly exposed nature of the region. The folding pattern of the Middle to Upper Miocene sedimentary rocks is drawn in agreement with that determined from dip measurements in the field. These rocks are shown overlying the older rocks with an angular unconformity. It is not clear whether the mélanges of the Lahewa Sub-basin formed during the Early Miocene uplift event or at a later stage because cross-cutting relationships have not been discovered during this study and are not reported by previous workers. Evidence from the Mujoi and Gomo sub-basins shows however that in these areas the mélanges largely formed during the Pliocene.

CONCLUSIONS

The work outlined above indicates that Nias cannot be viewed as a classical accretionary prism. The structure over a large part of the island is simply monoclinal and elsewhere, in general, structures verge to the northeast. Basin formation occurred during the Oligocene and Early Miocene subsequent to the emplacement of ophiolitic material into the forearc. These basins formed under an extensional or transtensional regime rather than in a compressional environment. The subsequent compressional deformation recorded on Nias was not continuous; rather the deformation of the basin infill successions occurred during two distinct periods of compression; firstly during the Early Miocene when western areas of Nias were subject to uplift and secondly during the Pliocene when all the major faults on Nias were reactivated to varying extents.

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