The origin of the Woyla Terranes in Sumatra and the Late Mesozoic evolution of the Sundaland margin

A.J. Barber

SE Asia Research Group, Department of Geology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

Received 5 June 1999; accepted 29 April 2000

Abstract

The Jurassic–Cretaceous Woyla Group of northern Sumatra includes fragments of volcanic arcs and an imbricated oceanic assemblage. The arc rocks are intruded by a granitic batholith and are separated from the original continental margin of Sundaland by the oceanic assemblage. Rocks of the arc assemblage are considered to be underlain by a continental basement because of the occurrence of the intrusive granite and of tin anomalies identified in stream sediments. Quartzose sediments associated with the granite have been correlated with units in the Palaeozoic basement of Sumatra. From these relationships a model has been proposed in which a continental sliver was separated from the margin of Sundaland in the Late Jurassic to Early Cretaceous in an extensional strike-slip faulting regime, producing a short-lived marginal basin. The separated continental fragments have been designated the Sikuleh and Natal microcontinents. In the mid-Cretaceous the extensional regime was succeeded by compression, crushing the continental fragments back against the Sundaland margin, with the destruction of the marginal basin, now represented only by the imbricated oceanic assemblage. Modifications of this scenario are required by subsequent studies. Age-dating of the volcanic assemblage and intrusive granites in the Natal area showed that they formed part of an Eocene–Oligocene volcanic arc and are not relevant to the model. Thick-bedded radiolarian chert and palaeontological studies in the oceanic Woyla Group rocks of the Natal and Padang areas showed that they formed part of a more extensive and long-lived ocean basin which lasted from at least Triassic until mid-Cretaceous. This raised the possibility that the Sikuleh microcontinent might be allochthonous to Sumatra and encouraged plate tectonic reconstructions in which the Sikuleh microcontinent originated on the northern margin of Gondwanaland and migrated northwards across Tethys before colliding with Sundaland. Since these models were proposed, the whole of Sumatra has been mapped and units correlated with the Woyla Group have been recognised throughout western Sumatra. These units are reviewed and the validity of their correlation with the Woyla Group of northern Sumatra is assessed. From this review a revised synthesis for the Late Mesozoic tectonic evolution of the southwestern margin of Sundaland is proposed. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Indonesian island of Sumatra forms the southwestern margin of Sundaland, the Southeast Asian promontory of the Eurasian continental tectonic plate. At the present time the Indian–Australian plate is being obliquely subducted beneath this margin at a rate of ~7 cm/a\(^{-1}\). Geologically, Sumatra consists of a Pre-Tertiary continental basement, overlain by a number of oil and gas-bearing Tertiary sedimentary basins (Fig. 1). Towards the southwestern coast of the island the basement is uplifted, exposing Pre-Tertiary rocks in the Barisan Mountains. The Quaternary volcanic arc, with currently active volcanoes, has been constructed on top of this uplifted basement. All the rock units in Sumatra, Pre-Tertiary basin, Tertiary sediments and Recent volcanics, are cut by the dextral Sumatran strike-slip fault system which extends from NW–SE along the whole length of the island (Fig. 1). Earthquake activity indicates that movement along the fault, continues to the present day. The Sumatran Fault System is interpreted as the result of oblique subduction of the Indian Ocean Plate beneath Sumatra (Fitch, 1972).

The concept of the Woyla terranes, was developed from the interpretation of the mapping results of the ‘Integrated Geological Survey of Northern Sumatra’, conducted jointly by the Indonesian Directorate of Mineral Resources (DMR) and the British Geological Survey (BGS) between 1975 and 1980. This survey comprised geological and geochemical reconnaissance mapping of the whole of Sumatra to the north of the equator (Page et al., 1978). Among the results of the survey, a series of 16 geological map sheets at the scale of 1:250,000 with accompanying descriptive booklets, were published by the Indonesian Geological Research and Development Centre (GRDC), Bandung. A summary of the geology and the stratigraphy, with an interpretation of the tectonic development of Sumatra, based on the results of
this survey, were presented at the 9th Annual Convention of
the Indonesian Petroleum Association (Cameron et al.,
1980). Geological mapping of the southern part of Sumatra
by the Indonesian Geological Survey in collaboration with
the United States Geological Survey commenced in the
1970s and was completed by 1995 with the publication of
the last of 43 geological map sheets covering the whole of
Sumatra.

The DMR/BGS mapping programme commenced in
Aceh in northern Sumatra where three tectonostratigraphic
units forming the Pre-Tertiary basement were recognised:
the Permo-Carboniferous Tapanuli Group; the Permo-Trias-
sic Peusangan Group; and the Jurassic–Cretaceous Woyla
Group. As mapping proceeded southwards similar units,
covering the same age ranges, were recognised and corre-
lated with those of northern Sumatra. Subsequently, units
resembling the Woyla Group and with the similar ages have
been identified throughout the whole of the western part of
Sumatra (Fig. 1). Rock units correlated with the Woyla
Group are described from Natal in North Sumatra, at Indar-
ung and Siguntur near Padang in West Sumatra, in the
Gumai and Garba Mountains of South Sumatra, and further
south near Bandarlampung along the Sunda Strait.

In the north, the Woyla Group and its correlatives lie
largely to the southwest of the Sumatran Fault Zone,
while to the south, they are only exposed to the northeast
of the fault zone. In this contribution, the extent to which
these units have been correctly correlated with the Woyla
Group, the interpretations which have been proposed for the
origin of the Woyla Group and its correlatives, and the
validity of the concept of the Woyla terranes, will be
discussed and re-examined in the context of the tectonic
evolution of the southwestern margin of Sundaland during
the Late Mesozoic.

2. Woyla Group in Aceh

The Woyla Group was defined in Aceh, northern Suma-
tra, where these rock units are extensively exposed in the
Barisan Mountains (Fig. 2). Areas of outcrop of the Woyla
Group are shown on the GRDC Banda Aceh, Calang,
Tapaktuan and Takengon 1:250,000 Quadrangle Sheets (Bennett et al., 1981a, b; Cameron et al., 1982, 1983). The descriptions given below, except where specified, are taken largely from the reports which accompany these maps. The Woyla River, from which the Woyla Group was named, is on the Takengon Sheet (Fig. 2).

During the DMR/BGS survey 13 lithostratigraphic units were distinguished in the Woyla Group, as well as a unit of ‘undifferentiated Woyla’. These units generally occur as fault-bounded lenses, distributed on both the northeastern and southwestern sides of the Sumatran Fault, and are elongated in a NW–SE direction, parallel to the Sumatran trend. The Woyla Group is also affected by several thrusts; the Geumpang, Takengon and Kla lines. The distribution of these units and the outcrops of the thrusts are shown on Fig. 2.

2.1. Lithological units in the Woyla Group

2.1.1. Tangse Serpentinite (Cahop Serpentinite, Beatang Ultramafic Complex–Takengon Sheet)

Massive serpentinite, representing altered harzburgite, occurs as lenses along the Sumatran Fault and along the Geumpang Line. The largest of these lenses extends discontinuously for 27 km to the northwest of Tangse. Chromite occurs in float in streams near this locality. Here and elsewhere, serpentinite is locally sheared, schistose, twisted and contorted. Sheared serpentinite may also form the matrix to mélangé (Indrapuri Complex). The mélangé encloses blocks of cumulate gabbro, basalt, red chert and limestones, derived from other members of the Woyla Group. Fossils collected from limestone blocks within the mélangé include: corals: Latoceandra ramosa, Stylina girodi; foraminifera: Pseudocyclamina sp.; stromatoporoid: Stromatopora japonica, indicating a Late Jurassic to Early Cretaceous age. In the Takengon Quadrangle large blocks of limestone enclosed in sheared serpentinite along the Geumpang Line, contain Late Miocene fossils (Cameron et al., 1983).

2.1.2. Penarum Formation

Outcrops to the northeast of the Sumatran Fault, south of Takengon, and consists of serpentinites, basalts, red cherts with radiolaria and slates. Volcanic rocks are commonly altered to greenschists.
2.1.3. Geumpang Formation (Banda Aceh Sheet); Babahrot Formation (Tapaktuan Sheet)

Outcrops occur, on both sides of the Sumatran Fault to the southeast of Banda Aceh and to the northwest of the Anu-Batee Fault towards Tapaktuan (Fig. 2). Rock types include massive or schistose basic volcanics, pillow basalts, volcaniclastic sandstones and tuffs, commonly epidotised and altered to greenschists or phyllites, and thin grey or black limestones. The phyllites are usually linedated and crenulated, indicating multiple deformation. The rocks of the Geumpang Formation are considered to constitute the typical lithological and structural assemblage of the Woyla Group. The Geumpang Formation also includes a massive limestone member, frequently occurring as marble.

The Babahrot Formation, north of Tapaktuan includes serpentinites and tcalc schists, as well as metagabbroic bodies metamorphosed in the greenschist facies, highly disrupted and sheared into lenses.

2.1.4. Lam Minet Formation (Banda Aceh Sheet); Gume Formation (Takengon Sheet)

Composed of basaltic lavas, commonly epidotised, basaltic conglomerates and breccias, with volcanic and limestone clasts, but only rarely chert, graded volcaniclastic wackes, radiolarian cherts with manganese oxide veining, rhodonite, and calcareous, manganiferous and carbonaceous slates. A clast of radiolarian chert, embedded in a volcanic conglomerate with flattened clasts, was collected by Nick Cameron (personal communication, 1999) in the Kreung Baro, Aceh, from a landslide within the outcrop of this formation. This occurrence indicates that volcanic rocks were erupted through ocean floor sediments, perhaps during the formation of a seamount. The formation also includes a recrystallised limestone member.

2.1.5. Jaleuem Formation

Outcrops occur 100 km to the southeast of Banda Aceh, on both sides of the Sumatran Fault. Composed largely of slates, but red cherts occur in float and the unit also includes a limestone member. Rb/Sr dating on 11 samples of slate gave 99 ± 30 Ma (late Early Cretaceous).

2.1.6. Bale Formation

Shown outcropping to the northwest of the Sumatran Fault, and southeast of Takengon. Composed of coloured slates, with minor wackes and cherts, limestones and limestone breccias.

2.1.7. Sise Limestone Formation

Consists of massive or bedded limestones, biocalcarenites and calcilutites with fossils: corals: Montlivaltia sp., Myriopora sp.; foraminifera: Pseudocyclamina sp. indicating a Late Jurassic to Early Cretaceous age.

2.1.8. Bentaro Volcanic Formation (Banda Aceh Sheet); Tapaktuan Volcanic Formation (Tapaktuan Sheet)

Porphyritic basalts and andesite basalts with agglomerates, intruded by basic dykes. Basaltic vents surrounded by breccias, tuffs and volcaniclastic sediments have been identified near Lam No and north of the Bentaro River on the Banda Aceh Sheet. Chemical analysis of a xenolith, porphyritic basalt with pyroxene phenocrysts is given in Rock et al. (1982).

The Tapaktuan Volcanic Formation occurs in fault-bounded lenses, within strands of the Anu-Batee Fault Zone, parallel to the west coast of Aceh north of Tapaktuan. It consists of massive epidotised andesites and basalts, commonly porphyritic, and intrusive dykes of a similar composition. An analysis of hornblende microdiorite from this formation is given in Rock et al. (1982). The formation also includes agglomerates, breccias, tuffs, red and purple volcaniclastic sandstones and shales, the latter often as slates, and a limestone member, composed of sparite and calcilutite, all as lenses and much disrupted by faults.

Scattered outcrops of gneiss (Meukuk Gneiss Complex) occur within the Tapaktuan Volcanic Formation in the Barisan Mountains to the north of Tapaktuan, between strands of the Anu-Batee Fault (Fig. 2). They consist of concordant leucogranodioritic gneiss, with garnet-biotite amphibolite containing garnets up to 8 cm in diameter, and biotite-hornblende-andesine schist.

2.1.9. Lho'nga Formation

Outcropping to the west of Banda Aceh and composed of grey and coloured slates and phyllites, with interbedded volcaniclastic sandstones, thin limestones and (?) radiolarian-bearing siltstones.

2.1.10. Lhoong Formation

Forms a large outcrop to the southwest of the Sumatran Fault and also occurs as roof pendants in the Sikuleh Batholith (Bennett et al., 1981b). It consists of basaltic lavas with cherts in the lower part of the sequence, followed by conglomeratic wackes with volcanic and limestone clasts, and subordinate sandstones, siltstones and limestones.

2.1.11. Raba Limestone Formation

Outcrops along the coast and in the Barisan Mountains to the south of Banda Aceh and consists of massive calcarenite and calcilutite and dark thin-bedded cherty limestones and shales. The massive limestone constitutes a ‘reef member’ which is closely associated in the field with the Bentaro Volcanic Formation.

2.1.12. Lamno Limestone Formation

Outcrops along the west coast of Aceh, south of Banda Aceh, where it is associated with outcrops of the Bentaro Volcanic Formation. Consists of dark limestone, which includes a reef-like facies, and contains volcanic clasts near the base. The limestone is commonly fossiliferous,

2.1.13. Teunom Limestone Formation
Outcropping along the southwestern margin of the Siku- leh Batholith. Composed of massive dark limestones, meta- morphosed and recrystallised along the contact with the granite.
‘Undifferentiated’ Woyla Group rocks are shown on the Calang Quadrangle Sheet in the area to the south of the Sikuleh Batholith in Gunung Paling and as roof pendants within the outcrop of the batholith (Bennett et al., 1981b). In the Explanatory Note to this sheet these rocks are said to resemble the Kluet Formation, low-grade Carboniferous metasediments of the Sumatran basement, which outcrop extensively to the northeast of the Sumatran Fault. The implication here is that these rocks are composed of slates with interbedded quartzose sandstones. They are also reported to include quartzite (Bennett et al., 1981b). Quartzose rocks are otherwise unknown in the Woyla Group.

Many of the mapping units distinguished in the Woyla Group of Aceh during the DMR/BGS survey are made up of the same rock types but in varying proportions. It is clear that they represent geographical, rather than genuine lithostratigraphical units. A different name was given to each distinguishable unit on each map sheet. The actual lithological units within each formation are, on the whole, too small to be represented on the scale of the map.

2.2. Folds and related structures
The rocks of the Woyla Group in Aceh commonly show the effects of intense deformation. The finer grained sedi- mentary and volcanioclastic rock types have been altered to slates and phyllites. Isoclinal folds can be seen wherever bedding lamination can be distinguished, with axial plane cleavage parallel to bedding, and a bedding/cleavage inter- section lineation plunging to the SE. Slaty cleavage may be refolded, into more open folds on sub-horizontal axes and NE-dipping axial planes, with the development of secondary cleavages, lineations and kink band folds. Larger kilo- meter scale upright folds, up to ~7 km, on NW–SE trending axes and steep axial planes are reported from the Tapaktuan Volcanic Formation, with secondary folds on the scale of ~1–2 km (Cameron et al., 1982).

Massive limestone units in the Woyla Group are less obviously internally deformed, although mylonitised and kink-banded limestones are seen near Banda Aceh. Bedded limestones are sometimes folded on a large scale, as seen in quarries in the Lho’nga Formation between Banda Aceh and Lho’nga (Bennett et al., 1981a). Also in the same area, limestones interbedded with shales show pinch and swell structures, boudinage and the development of tension gashes normal to the bedding.

On the map scale all the units in the Woyla Group are fault-bounded and form large scale lenses elongated in a NW–SE direction parallel to the Sumatran trend. Internally the units are disrupted by large numbers of faults. Some of these faults are thrusts, along which rock units have been imbricated; others show slickensided surfaces indicating strike-slip movement along faults parallel to, and probably related to the Sumatran Fault System.

2.3. Sikuleh Batholith
The Woyla Group is intruded by granitoids, the largest of which is the Sikuleh Batholith, illustrated on the Banda Aceh and Calang sheets (Bennett et al., 1981a, b). This is an approximately elliptical body (~55×35 km) elongated in a NW–SE direction (Fig. 2). Around the margins of the batholith, ‘undifferentiated’ Woyla Group rocks and lime- stones of the Teunom Formation, have been altered by contact metamorphism. Roof pendants of metamorphosed Woyla Group rocks, shown as ‘undifferentiated’ on the map, but compared to the Lhoong formation, occur within the batholith (Bennett et al., 1981b). Rocks of the Geumpang Formation are thrust over the northeastern margin of the batholith along the Geumpang Line.

Although no attempt was made during the mapping to delineate the various components of the batholith, descriptions show that it is a complex and highly variable body (Bennett et al., 1981b). An ‘older complex’ is distinguished in the northern part of the complex, composed of dark and xenolithic gabbroic and dioritic bodies, migmatitic and intensely veined. The older complex is locally gneissose or sheared. Where foliation is developed, it is parallel to the foliation in the adjacent Geumpang Formation rocks. The ‘younger complex’, which has an intrusive contact against the earlier complex, is a more homogeneous, coarser grained and largely unfoliated, biotite-hornblende grano- diorite, with minor amounts of diorite and pink granite.

The granodiorite contains mafic xenoliths and becomes more mafic towards its margins, where it shows ‘flow folia- tion’. The granodiorite and is cut by pegmatites and aplites, the latter being more common adjacent to the contact with the older complex. The batholith shows ‘porphyry-type’ molybdenum mineralisation and tin anomalies of 10–80 ppm have been identified from stream sediment sampling along the contact between the older and younger complex, although no primary tin mineralisation has been recognised (Stephenson et al., 1982). The younger complex has been dated from the mean of K/Ar analyses on two biotites and one hornblende, as 97.7 ± 0.7 Ma (early Late Cretaceous) (Bennett et al., 1981b). The complex is cut by later basic dykes.

2.4. Thrusts
Bennett et al. (1981a, b) and Cameron et al. (1980, 1983)
recognised three major thrust zones in northern Sumatra (Fig. 2):

2.4.1. Takengon Line
This thrust has an E–W outcrop to the south of Lake Tawar, where it brings Permo-Triassic rocks of the Peusangan Group on top of the Penarum Formation of the Woyla Group along a flat-lying, southward-directed thrust plane. To the west of Takengon, along the continuation of this line, Miocene rocks are thrust over the Woyla Group.

2.4.2. Kla Line
A northwards-directed thrust plane, outcropping to the south of Takengon between the main Sumatran Fault and the Anu-Batee Fault, brings Permo-Carboniferous Tapanuli Group rocks onto ‘undifferentiated’ Woyla Group. Mylonites are developed along the thrust plane.

2.4.3. Geumpang Line
In the area to the southeast of Banda Aceh, units of the Woyla Group are separated by an easterly dipping thrust, the Geumpang Line, which outcrops parallel to the Sumatran Fault, and has the same NW–SE trend. Here members of the Woyla Group have been thrust southwestwards over Late Miocene sediments, the northeastern margin of the Sikuleh Woyla Group have been thrust southwestwards over Late Miocene rocks which were reactivated during Late Tertiary or Quaternary movements along the Sumatran Fault Zone. They suggest that serpentinite mélanges, commonly found along the fault and thrust planes, were derived from mantle peridotite thrust beneath the margin of Sundaland, which was hydrothermally mobilised and rose diapirically along fault and thrust planes during subsequent fault movements.

2.5. Interpretation of the Woyla Group in Aceh
Cameron et al. (1980) distinguished two lithological assemblages in the Woyla Group in Aceh: an oceanic (ophiolitic) and an (volcanic) arc assemblage. The distribution of these assemblages is represented on the ‘Simplified Geological Map of Northern Sumatra’ (Stephenson and Aspden, 1982):

2.5.1. Oceanic assemblage
This includes serpentinised harzburgite, metagabbro, mafic to intermediate volcanics, often basaltic and showing pillow structures, volcanic breccias, volcaniclastic sandstones, red and purple manganiferous slates, red radiolarian cherts. These rock types also occur as blocks in breccioconglomerates or mélanges.

Units of the oceanic assemblage include the Tangee and Cahop serpentinites, the Beatang Ultramafic Complex and the Penarum, Geumpang, Babahrot, Lam Minet, Jaleueum and Bale formations. All these units lie to the northeast of the Geumpang Line, and almost entirely to the northeast of the Sumatran Fault Zone (Fig. 2). Unfortunately, no age-diagnostic radiolarians have yet been obtained from the many occurrences of bedded (?radiolarian) chert which occur among these units, so that their age(s) has not been established directly. Limestone blocks in serpentinous mélange along the Geumpang Line, which yielded Late Jurassic to Early Cretaceous fossils, were ascribed to the Geumpang Formation (Cameron et al., 1983), but are more reasonably regarded as derived tectonically from underlying limestone units during the thrust movements, in the same way as Late Miocene blocks which are also included in the mélange.

The oceanic assemblage of the Woyla Group in Aceh shows an intimate mixture of ocean floor materials from different structural levels, from mantle to abyssal sediments, variously internally deformed, separated by faults, often identified as thrusts and arranged in a random order. These are the characteristic features of an accretionary complex, where ocean floor materials are imbricated against the hanging wall of a subduction zone. Garnetiferous amphibolites of the Meukuk Gneiss in the Tapaktuan Volcanic Formation suggest that gabroic rocks of the oceanic assemblage were subducted into the mantle, before being returned tectonically to the surface.

2.5.2. Arc assemblage
This is typified by the Bentaro and Tapaktuan Volcanic Formations, and is composed of porphyritic andesite, occurring as vents near Bentaro, basalt lavas, intrusive dykes, agglomerates, breccias, volcaniclastic sandstones and shales.

These igneous rocks are closely associated in the field with massive or bedded limestones, which commonly contain volcanic clasts or are interbedded with volcaniclastic units. These limestone units include the Lho’nga, Raba, Lamno, Lhoong, and Teunom Limestone formations, as well as the limestone lenses which occur within the Tapaktuan Volcanic Formation. Most of the units belonging to the arc assemblage lie to the southwest of the Geumpang Line and the Sumatran Fault. The only exception to this distribution, according to the geological map of Stephenson and Aspden (1982), is the Sise Limestone Formation, outcropping to northeast of the Sumatran Fault, to the south of Takengon (Fig. 2). This anomaly can be removed by reversing displacement along the Sumatran Fault. The Lamno and Sise limestones and the ‘Geumpang’ limestone blocks within the Indrapuri Complex all contain fossils which indicate a Late Jurassic–Early Cretaceous age.

Cameron et al. (1980) suggest that the intrusive and volcanic rocks represent the remnants of a Late Jurassic–Early Cretaceous volcanic arc. This arc emerged above sea level, where it was eroded to form breccias and volcaniclastic sediments. The arc was surrounded and overlain by a
fringing reefs represented by the massive limestones. In this model, massive limestones were eroded to form limestone breccias, and detritus was transported into deeper water to form bedded limestones. Cameron et al. (1980) put forward evidence which indicated that the volcanic arc was built up on a sliver of continental crust. The observation of a volcanic breccia containing radiolarian chert clasts in the Lam Minet Formation indicates that volcanic rocks were sometimes extruded through ocean floor sediments.

2.6. The marginal sea model

Cameron et al. (1980), noting the absence of a mid-Cretaceous magmatic arc in the eastern part of northern Sumatra, rejected the interpretation that the oceanic assemblage of the Woyla Group represents the accreted remnants of older segments of the ‘Indian Ocean’ in an earlier stage of the subduction process which continues today offshore southwest Sumatra. Instead, they interpreted the oceanic assemblage as the remnants of a short-lived marginal oceanic basin, developed along the southwestern margin of Sundaland in a phase of extreme oblique subduction and active strike-slip faulting, with the formation of a pull-apart basin and then oceanic crust.

The marginal basin was formed in Late Jurassic–Early Cretaceous times by the separation of a continental sliver from the western margin of Sundaland, in the same way as the Andaman Sea or the Gulf of California are being forming at the present time (Cameron et al., 1980, their Fig. 4a). The separated continental sliver is now represented by the Bentaro Volcanic Arc and the Sikuleh Batholith. Also associated with the batholith are ‘undifferentiated’ Woyla metasediments which resemble the Carboniferous Kluet Formation of the Sumatran basement, and tin anomalies. All these features are taken as evidence that the arc volcanics overlie continental crust. On the Tectonic Map of Northern Sumatra the basement underlying the arc assemblage is described as the Sikuleh Continental Fragment (Aspdén et al., 1982).

Subsequently, as a result of continuing subduction outboard of the continental fragment and transpressional strike-slip movement, this small marginal ocean basin was compressed, crushing both the floor of the marginal basin and the detached continental fragment against the Sundaland margin. The Takengon and Kru lines represent the thrust surfaces along which the materials of the marginal basin were thrust beneath the continental margin of Sundaland. The suture, representing the site of this disappeared marginal basin, coincides approximately with the line of the present day Sumatran Fault. Also, as the result of compression, the continental fragment and its overlying arc were thrust beneath the oceanic assemblage along the Geumgang Line (Cameron et al., 1980).

Although there is no direct evidence for the age of the ocean floor materials, and the age of the volcanic arc is established only from the palaeontological dating of its fringing reefs, all these events are considered to have occurred between the Late Jurassic and Late Cretaceous. It is suggested that rifting of the continental margin and the formation of the volcanic arc occurred in the Late Jurassic and the opening of the marginal basin took place in the Early Cretaceous. The intrusion of the Sikuleh Batholith into both the oceanic and the arc assemblages shows that the closure of the basin and the compression of the arc against the continental margin was completed by Late Cretaceous times (Cameron et al., 1980).

Woyla Group rocks which took part in these events are now sliced into lenticular slivers by more recent movements along the Sumatran Fault (Cameron et al., 1980). In the field it is difficult to distinguish between thrust faults which were formed by the imbrication of the units during subduction, and later strike-slip faults related to the Sumatran Fault System unless slickensides are present. It is impossible to distinguish between strike-slip faults formed as the result of oblique subduction and those due to later fault movements (Wajzer et al., 1991).

As has already been suggested, the anomalous position of the massive limestones of the Sise Limestone Formation, which now lie on the northeastern side of the main strand of the Sumatran Fault, may be the result of movements along the fault. The Sise Limestone Formation and the Lamno Limestone Formation near Banda Aceh, contain similar fossil assemblages and are of the same age. Reversing the dextral movement along the fault for a distance of ~200 km would bring the Sise and Lamno formations into juxtaposition. This order of movement along the Sumatran Fault is compatible with the evidence from regional considerations, with a 460 km movement in the Andaman Sea reducing southwards to a displacement of only a few kilometres in the Sunda Strait (Curry, 1989; McCaffrey, 1991). Strike-slip fault movements along the Sumatran Fault System are also considered to have reactivated fundamental thrusts in the basement along the Takengon, Kla and Geum-pang lines, as Neogene rocks are affected by this movement, in transpressional zones along strands of the fault system (Cameron et al., 1980).

3. Woyla Group in Natal

Rocks correlated with the Woyla Group of Aceh were mapped over an extensive area inland from Natal in North Sumatra during the Integrated Geological Survey of Northern Sumatra as part of the Lubuksikaping 1:250,000 Quadrangle Sheet (Rock et al., 1983) (Fig. 3). The outcrop is limited to the northeast by the Sumatran Fault System and is much dissected internally by faults with a similar trend. The Woyla Group is intruded by Late Cretaceous granites and overlain unconformably by the Miocene Barus Group, by Miocene volcanic rocks, and by the products of Quaternary volcanism from the volcanoes of Sorik Merapi, Malintang and Talaman, as well as by recent alluvium. Units within the Woyla Group strike NW–SE and are very well
exposed in the valley of the Batang Natal, both in the river section and in the parallel road section, which both cut across the strike (Fig. 4). The main outcrop of the Woyla Group is separated from a smaller outcrop in the Pasaman inlier to the south by Malintang Volcano (Fig. 3).

3.1. DMR/BGS report

In the DMR/BGS report of the Lubuksikaping Quadrangle (Rock et al., 1983) lithological units in the Batang Natal section were classified, from NE–SW, into three formations: the Maurosoma, Belok Gadang and the Sikubu formations (Fig. 3).

The Maurasoma Formation outcrops in the upstream part of the section and in its tributary the Aik Soma. Thicknesses of the rock units in this section were measured perpendicular to the strike for a distance of 5.5 km (Rock et al., 1983). The rock types include cleaved argillaceous units, shale or slate, which may include calcareous concretions, laminated siltstones, and gritty sandstones showing sedimentary structures, indicating younging in a downstream direction, massive limestones, sometimes forming limestone pinacles, epidoetic volcanic breccias and volcaniclastic sandstones, chloritic greenschists and muscovite-chlorite quartz schists. A 10 m ‘conglomerate’ (?) mélangé at the upstream end of the section, with elongated clasts of greenschist in a chloritic matrix, is probably of tectonic origin, formed in a fault or a shear zone (Rock et al., 1983).

The Belok Gadang Formation outcrops in the central part of the section and is composed of sandstones, sometimes calcareous, and argillaceous rocks, often cleaved and containing bands and lenses of chert. The chert is radiarian, but no identifiable radiolaria have so far been recovered which could be used to date the sequence. Outcrops in the type locality of Belok Gadang, a tributary of the Batang Natal, show basaltic pillow lavas, with white clay interbeds and manganese-rich horizons with braunite, resembling the ‘umbers’, described from the Troodos Ophiolite of Cyprus (Robertson, 1975). Analysis shows that the pillow basalts are spilites (Rock et al., 1982, 1983). In the type locality basalts are overlain by red, bedded cherts, but again no identifiable radiolaria have been recovered.

The Sikubu Formation, outcropping in the lower part of the Batang Natal section, is composed of massive volcaniclastic metagreywackes, with thin shale interbeds. The sandstones show very well-developed sedimentary structures, including graded bedding, flame structures and convolutions, typical of turbidites. Massive porphyritic andesitic dykes and lava flows, with distinctive pyroxene phenocrysts, are intruded into or interbedded with the sediments in the lower part of the section. Fragments of porphyritic andesite, identical in composition to the dykes and lavas, occur as clasts in the sandstones.

Woyla Group rocks in the Pasaman area include mélanges and massive and foliated peridotites (Rock et al., 1983) (Fig. 3). Peridotites are well exposed in the
Pasaman River where they are composed mainly of harzbur- gite with minor dunite pods, pyroxenite dykes, disseminated chromite and rare chromite pods. Some of the peridotite is foliated, containing orthopyroxenes enclosed in augen. Coarse plagioclase-hornblende rocks, found as boulders in the float, represent metasomatised gabbro pegmatite which formed dykes in the peridotite. The peridotite is variably serpentinised, and in shear zones may be completely altered to serpentine and talc. Smaller bodies of serpentinite, with chromite pods, outcrop at the upper end of the Batang Natal section near Maurasoma (Figs. 3 and 4) where they form spectacular serpentinite breccias faulted against slates and limestones of the Maurasoma Formation. Serpentinite also occurs as xenoliths in granite in the Aik Soma.

3.2. Langsat Volcanic Formation

Porphyritic, net-veined and amygdaloidal basic lavas of the Langsat Formation, associated with agglomerates, outcrop at the southwestern end of the Batang Natal section (Rock et al., 1983) (Fig. 3). The lavas are melanocratic but contain leucocratic xenoliths. The basic rocks are highly porphyritic, with abundant clinopyroxene phenocrysts, but show very little plagioclase in thin section; the dominant feldspar in the ground mass being orthoclase. Analyses show that these lavas have a highly unusual chemical composition with low SiO₂ and high MgO contents (Rock et al., 1982, 1983). Exceptionally high contents of Cr, Ni and Co are correlated with the abundance of augite. The absence of hypersthene, the lack of plagioclase and the presence of orthoclase, together with the overall chemical composition, shows that these lavas are absarokites (basic shoshonites) (Rock et al., 1983).

3.3. Late Mesozoic intrusions

Several large granitoid bodies are intruded into the rocks of the Woyla Group in the Natal area. The largest is the Manunggal Batholith at the northeastern end of the Batang Natal section (Rock et al., 1983) (Fig. 3). This batholith is a composite body, some 230 km² in extent, composed of leucogranodiorite, granodiorite, granite, pyroxene-quartz diorite with contaminated syenitic and monzonitic varieties, and appinites. The granitoid rocks are intruded by vogesite lamprophyre dykes. This granitoid has been dated by the K/Ar method at 87 Ma (Late Cretaceous) (Kanao et al., 1971, reported in Rock et al., 1983). In the Aik Soma, near Maurasoma, large granitic boulders in the river bed enclose serpentinite xenoliths, surrounded by reaction zones of
amphibolite. Limestones in the same area are converted to skarns near the contact with the granite.

A second granitoid, the Kanaikan intrusion, is intruded into the Woyla Group in the Pasaman area (Fig. 3). This body is composed of coarse granodiorite and leucogranite cut by microgranitic and granophyric dykes. The intrusion lies within the Kanaikan Fault Zone, a strand of the main Sumatran Fault, and is much dissected by faults and deformed to cataclasite along shear zones.

3.4. Palaeogene intrusions

Granitic rocks form scattered outcrops in headlands near Air Bangis, along the coast to the south of Natal (Fig. 3). A large area inland of these outcrops on the Lubuksikaping Sheet is also shown as occupied by granitoid. This inland outcrop is largely conjectural, as the interpretation is based on aerial photographic interpretation, and much of the area is covered by cloud on the photographs used in the interpretation (Rock et al., 1983). The coastal outcrops are composed of hornblende-biotite adamelites, leucogranites and granites, cut by microgranitic and microdioritic dykes. These intrusions are shown on the Lubuksikaping Sheet as of Eocene–Oligocene age. However, Rock et al. (1983) in their report, speculate that these intrusions might be of Late Cretaceous age, analogous to the Sikuleh intrusion which occupies a similar position with respect to the Woyla Group in Aceh.

3.5. Age constraints in the Natal area

Age constraints for the Woyla Group in the Natal area are provided by a limestone sample from the Batang Kanaikan in the Pasaman inlier which yielded a colonial organism, closely resembling the samples of *Lovcenipora* described and illustrated by Yancey and Alif (1977) from the Indarung area, near Padang, and considered to be of Late Jurassic to Early Cretaceous age (IGS/British Museum Sample No.TC/J1/R1101B—Rock et al., 1983). A minimum age for the Woyla Group is provided by the Manunggal Batholith, dated at 87.0 Ma (Late Cretaceous) (Kanao et al., 1971, quoted in Rock et al., 1983), which intrudes limestones and serpentinites at the northwest end of the Batang Natal section.

3.6. Interpretation — the marginal sea model

The model developed by the DMR/BGS mapping team to explain the origin and tectonic environment of the Woyla Group in Aceh was extended southwards, with minor modifications, to account for the distribution of similar rock assemblages of Jurassic to Cretaceous age outcropping in the Natal area of North Sumatra (Rock et al., 1983).

Rock et al. (1983) interpreted the Maurosoma Formation at the northeastern end of the section, which includes turbidites and massive limestones, as shelf sediments of the Sundaland continental margin. The Belok Gadang Formation, with pillow basalts and cherts, was interpreted as the deformed floor of the marginal basin, and the Sikuba Formation in the southwest as the erosion products of a volcanic arc. The arc itself is represented by the the Langsat Volcanics which outcrop at the southwest end of the Batang Natal section (Rock et al., 1983) (Figs. 3 and 4). As in Aceh, the arc was considered to overlie continental basement and constitutes a microcontinental block, identified in the ‘Tectonic Map of Northern Sumatra’ as the Natal Continental Fragment (Aspden et al., 1982). The Air Bangis granitoids, considered to be intrusive into the Langsat Volcanics, although this relationship is not actually observed, are regarded as evidence that the arc is underlain by continental crust. Again, using the age constraints provided by the occurrence of *Lovcenipora* in Woyla Group rocks in the Pasaman inlier and the age of intrusion of the Manunggal Batholith, Rock et al. (1983, their Fig. 8) postulate that between Late Jurassic and Early Cretaceous time, a pull-apart rift developed into a short-lived marginal basin along the margin of Sundaland, which was then compressed and destroyed by the Late Cretaceous. Rock et al. (1983) acknowledged that if the Cretaceous age ascribed to the Air Bangis granitoids was not correct, then the marginal sea model was invalid and the arc and its underlying continental basement might constitute a terrane allochthonous to Sumatra. In the key to the Lubuksikaping Map Sheet the Air Bangis granitoids are shown as of Late Cretaceous/Palaeogene age.

3.7. Wajzer study

The Batang Natal section was mapped in detail by Marek Wajzer from the University of London, in a follow-up study to the Northern Sumatra Survey, in collaboration with BGS and with the assistance of Syarif Hidayat and Suhasrono of GRDC (Wajzer et al., 1991). The mapping was supported by petrographic, geochemical and radiometric studies. Wajzer et al. (1991) found that the Woyla Group was not neatly divisible into three distinct lithological units, but that the same recognisable lithologies were repeated many times throughout the section, apparently in a random fashion (Fig. 4). Wajzer et al. (1991) distinguished 16 lithostratigraphical units in the Natal section. Correlation with the mapping units recognised by Rock et al. (1983) is shown in Table 1. Detailed accounts of the lithological units are given in Table 2. Many of the lithologies are similar to rock types described from the Woyla Group in Aceh, and by Rock et al. (1983), with the addition of several outcrops of mélangé, composed of blocks in a fine grained matrix, described as ‘megabreccia’ in Table 2 and Fig. 4. One important feature of the clastic units in the Woyla Group of the Natal area is that they are almost completely devoid of quartz, suggesting that they have an entirely oceanic, rather than a continental origin (Wajzer et al., 1991).

The study established several additional age constraints for the Woyla Group, using fossil evidence and radiometric
deformation, with the earlier isoclinal folds and schistosity folded by more open folds, and the development of secondary cleavages and lineations. Some units such as the Rante Sore Formation are completely unmetamorphosed, while metabasites show pumpellyite and actinolite, and schists contain coarse white micas, indicating metamorphism up to greenschist facies. There is no systematic progression either in intensity of deformation or in grade of metamorphism through the section, the units appearing to be randomly arranged (Wajzer et al., 1991).

Each of the units distinguished in the Woyla Group in the Natal River section is separated from adjacent units by steeply dipping or vertical faults. In addition units are frequently disrupted internally by faults, often every few metres. Some of the fault planes show vertical slickensides, indicating normal or reverse movement, while others show horizontal slickensides, indicating strike-slip movement (Wajzer et al., 1991).

3.10. Interpretation — the allochthonous terrane model

The Batang Natal section was reinterpreted by Wajzer et al. (1991). They pointed to the absence of any significant amount of quartz in the volcaniclastic sediments or any continental clastic material in the massive limestones of the Maurasoma Formation, and suggested that these deposits were of oceanic, rather than of continental margin origin. They concluded, from the extensive deposits of bedded radiolarian chert and associated manganiferous argillites, that the oceanic deposits represented accreted fragments of the floor of a major ocean basin, rather than the floor of a restricted marginal sea. As in Aceh, in the absence radiometric ages for the pillow basalts, or of diagnostic radiolaria in the chert, there is no direct evidence of the age of formation of the ocean floor. Wajzer et al. (1991) suggest that the volcanic units represent seamounts or fragments of volcanic arcs, and that limestone blocks in the mélanges represent fragments of the collapsed carbonate cappings to these seamounts, or fringing reefs to the arcs. Foraminifera in a limestone block in one of these mélanges suggest that a seamount was constructed on ocean floor which was at least as old as Triassic, and that therefore the ocean basin was already in existence in the early Mesozoic.

Wajzer et al. (1991), on the basis of interbedded lava flows and the occurrence of fragments of andesite in the conglomerates, recognisably derived from the Langsat Volcanics, accepted the interpretation of Rock et al. (1983) that the Si Kumbu Turbidite Formation (their Sikubu Formation) was contemporaneous with the Langsat Volcanics, and that the volcanics and volcaniclastic turbidites represent a volcanic arc. Andesite dykes intruded into the Si Kumbu Formation, of similar composition to the lavas, gave radiometric dates of 37.6 and 40.1 Ma (Late Eocene) (Wajzer et al., 1991). As has already been reported, Rock et al. (1983), following the marginal sea model from Aceh, suggested that the Air Bangis granitoids, which are presumed to be intruded into

![Table 1: Correlation of formations in the Woyla Group of the Natal area from Rock et al. (1983) with lithotectonic units defined by Wajzer et al. (1991)](https://example.com/table1.png)

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Langsat Volcanic Formation</td>
<td>1. Langsat Volcanic Formation</td>
</tr>
<tr>
<td>2. Sikubu Formation</td>
<td>2. Si Kumbu Turbidite Formation</td>
</tr>
<tr>
<td>3. Belok Gadang Formation</td>
<td>3. Tambak Baru Volcanic Unit</td>
</tr>
<tr>
<td>5. Belok Gadang Siltstone Formation</td>
<td>5. Belocho Mélange Formation</td>
</tr>
<tr>
<td>6. Andesite dykes intruded into the Si Kumbu Formation</td>
<td>6. Ranto Sore Formation</td>
</tr>
<tr>
<td>7. Panglong Mélange Formation</td>
<td>7. Rantobi Sandstone Formation</td>
</tr>
<tr>
<td>8. Parlampungan Volcanic Unit</td>
<td>8. Jambor Baru Formation</td>
</tr>
<tr>
<td>10. Si Gala Gala Schist Formation</td>
<td>10. Ranto Sore Formation</td>
</tr>
<tr>
<td>11. Simarobu Turbidite Formation</td>
<td>11. Jambor Baru Formation</td>
</tr>
<tr>
<td>13. Rantobi Sandstone Formation</td>
<td>13. Batu Nabontar Limestone Unit</td>
</tr>
<tr>
<td>15. Maurasoma Turbidite Formation</td>
<td>15. Batu Nabontar Limestone Unit</td>
</tr>
<tr>
<td>16. Batu Nabontar Limestone Unit</td>
<td>16. Batu Nabontar Limestone Unit</td>
</tr>
</tbody>
</table>

* Units are listed in approximate order upstream from Langsat (see Fig. 4) with no age relationship implied.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Environment</th>
<th>Structure</th>
<th>Metamorphism</th>
<th>Age constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langsat Volcanic Unit</td>
<td>Porphyritic basic volcanics</td>
<td>Arc volcanics</td>
<td>No ductile deformation</td>
<td>Prehnite-pumpellyite</td>
<td>Possibly intruded by Air Bangis Granites. K/Ar 28.2 Ma, 29.7 Ma</td>
</tr>
<tr>
<td>Si Kumbu Turbidite</td>
<td>Volcaniclastic debris flows, proximal and distal turbidites</td>
<td>Submarine fan — apron to volcanic arc</td>
<td>D2 large scale folds (F2) on WNW–ESE axes</td>
<td>Prehnite-pumpellyite</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td>Prehnite-pumpellyite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tambak Baru Volcanic</td>
<td>Andesitic volcanics</td>
<td>Fragments of volcanic arc and proximal volcanoclastics</td>
<td>D1 weak foliation (S1),D2?</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Simpang Gambir Megabreccia Formation</td>
<td>Volcanic breccia with limestone megaclasts and greywacke sandstones</td>
<td>Proximal sediments derived from volcanic arc, with olistostromes</td>
<td>D1 strong foliations (S1),D2 open folds and crenulations (F2)</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Nabana Volcanic Unit</td>
<td>Basic volcanies (sometimespillowed) amygdaolidal to E, keratophyres, dolerite dykes</td>
<td>Ocean-floor basalts, seamound</td>
<td>No ductile deformation</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Panglong Mélange</td>
<td>Breccias with chert, Mn sedim., limestones and volcanic clasts in chert siltstone matrix</td>
<td>Mélangé (?olistostome) of ocean-floor materials and pelagic sediments</td>
<td>D1 tight to isoclinal folds (F1), D2 open to close folds (F2) fold F1 on NW–SE axes</td>
<td>Slate grade</td>
<td>Older than Belok Gadang siltstone</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belok Gadang Siltstone</td>
<td>Volcaniclastic siltstones with few fine sandstones and rare conglomerates</td>
<td>Unconformable on Panglong Mélange. ?Lower trench slope basin fill</td>
<td>Dipping beds with no ductile deformation</td>
<td>Prehnite-pumpellyite</td>
<td>Younger than Panglong Mélange Formation</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ranto Sore Formation</td>
<td>Volcaniclastic cross-bedded and channelled sandstones and unsorted conglomerates (lahars)</td>
<td>Fluviatile intra-arc deposits</td>
<td>D2 open to close folds (F2) on NN–SSE axes</td>
<td>Unmetamorphosed</td>
<td>?Younger than adjacent units</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parlumpangan Volcanic</td>
<td>Porphyritic andesites</td>
<td>Fragments of volcanic arc</td>
<td>No ductile deformation</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Si Gala Gala Schist Unit</td>
<td>Banded quartz, muscovite, chlorite schists</td>
<td>Metasediments derived from acid-intermediate volcanic arc province</td>
<td>D1 schistosity (S1) and rodding (L1), D2 open to close folds (F2) on NW–SE axes</td>
<td>Greenschist</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simarobu Turbidite</td>
<td>Volcaniclastic turbidites with minor calcareous siltstones</td>
<td>Ocean-floor or trench deposit</td>
<td>Foliation (S1), D2 open to close folds (F2). D1 tight to isoclinal folds (F1) axial plane on NNE–SSE axes</td>
<td>Greenschist</td>
<td>Cut by undeformed micro-diorite dyke. K/Ar 49.5 ± 2 Ma (NR 7)</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batang Natal</td>
<td>Large clasts of limestone, rare clastic sediments and igneous rocks in slaty matrix</td>
<td>Mélange formed as olistostrome or as mud diapirs in accretionary complex</td>
<td>D1 tight to isoclinal folds (F1), D2 open to close folds deform S1 about NNE–SSW axes. D1 tight to isoclinal folds (F1) with axial plane foliation (S1), D2 open to close folds (F2) deform S1 on NN–SSE axes.</td>
<td>Slate grade</td>
<td>Included limestone clasts contain Late Triassic foraminifera. Intruded by Batu Madingding Diorite. K/Ar 84.7 ± 3.6 Ma</td>
</tr>
<tr>
<td>Megabreccia Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rantobi Sandstone</td>
<td>Thin bedded volcaniclastic sandstones and siltstone</td>
<td>Forearc basin deposits</td>
<td>Axial plane cleavage (S1). D1 isoclinal folds (F1) with D2 close asymmetric folds (F2)</td>
<td>Slate grade</td>
<td>–</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jambor Baru Formation</td>
<td>Volcaniclastic conglomerate, sandstone, siltstone, limestone and tuff</td>
<td>Shallow marine and deeper water forearc basin deposits</td>
<td>D1 foliation (S1), D2 close folds (F2) on NW–SE axes</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Maurosoma Turbidite</td>
<td>Thin bedded volcaniclastic turbidites with a coarser grained member</td>
<td>Upper trench slope basin sediments</td>
<td>D1 foliation (S1), D2 folds (F2) on NW–SE axes</td>
<td>Prehnite-pumpellyite/</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
<td>greenschist</td>
<td></td>
</tr>
<tr>
<td>Batu Nabontar Limestone</td>
<td>Massive recrystallised limestone, rare fossils</td>
<td>Open marine shelf limestone</td>
<td>D1 tight folds in interbedded tuffs (F1), fossils show strain</td>
<td>Recrystallised</td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a All units are cut by numerous faults and thrusts. Vertical faults often show horizontal slickensides indicating wrench fault movements. *K/Ar age of Manunggal Batholith from Kanao et al. (1971). All other K/Ar ages from Wajzer et al. (1991).
these rocks have been correlated with the Woyla Group of Aceh by Cameron et al., 1980). Although as already pointed out they acknowledged that if the Late Cretaceous age for the Air Bangis granitoids was incorrect, then an allochthonous origin was probable. Wajzer et al. (1991) reversing the correlation, suggested that if the Natal Microcontinental Fragment is an allochthonous terrane, then it is possible that the Sikuleh Microcontinental Fragment although of a different age, is also allochthonous.

4. Other units in Sumatra correlated with the Woyla Group

Outcrops of rock units with similar lithologies to those of the Woyla Group or which were formed within the same Jurassic–Cretaceous age range have been mapped throughout western Sumatra (Fig. 1). Many of these outcrops have been correlated with the Woyla Group of northern Sumatra by previous authors.

4.1. Indarung formation

Small outcrops of the Mesozoic Indarung Formation occur near Padang in West Sumatra. These rocks were mapped and described by Yancey and Alif (1977) and were correlated with the Woyla Group of Aceh by Cameron et al. (1980). Outcrops occur 15 km east of Padang in road, river and quarry sections near Indarung, where they are surrounded and overlain by Neogene and Quaternary volcanic and volcanioclastic rocks (Fig. 5). The area of outcrop is included on the Padang, Solok and Painan Quadrangle Sheets (Kastowo and Leo, 1973; Silitonga and Kastowo, 1975; Rosidi et al., 1976). These rocks have been mapped more recently by McCarthy et al. (2001).

Yancey and Alif (1977) described rocks exposed in the Lubuk Peraku River, the Ngalau Quarry, the Karang Putih Quarry and adjacent river sections near Indarung. Rock types in these outcrops are basic volcanics, which may include pillow lava, volcanic breccia, tuff, volcanioclastic sediments, radiolarian chert and massive or bedded limestones. The basic rocks are sometimes deformed and metamorphosed to form greenschists. On the other hand, the limestones and cherts are essentially undeformed, although disharmonic folding and small scale thrusts in the chert and gentle folds in the limestone are seen in the quarries, and the limestones may be recrystallised (McCarthy et al., 2001).

A well exposed section of limestone and tuff occurs in the river section of the Lubuk Peraku and in the road above the river (Yancey and Alif, 1977; McCarthy et al., 2001). Bedding in the limestones has a steep, but variable dip to the southwest, and the section youngs in the same direction. A measured columnar section of these outcrops from McCarthy et al. (2001) is given as Fig. 6. The lower part of the section, described as the Lubuk Peraku Limestone, is a limestone breccia, which includes volcanic clasts near the base and is interbedded with thin tuff bands near the top. The breccia is overlain by a few metres of thin-bedded limestones and shelly marls and then by thicker bedded and more massive limestones, some oolitic. Near the top of the section a limestone conglomerate, eroded into the underlying limestone with basal scour, provides clear evidence of way-up. Above the breccia there is a break in the outcrop, until outcrops further downstream and in the road section above expose a calcareous vitreous crystal tuff, the Golok Tuff. Although the contact between the breccia and the tuff is not exposed, McCarthy et al. (2001) regard this section as an essentially continuous stratigraphic sequence, as tuff layers occur within the limestone breccia and tuffs within the overlying Golok Tuff unit are calcareous.

In the Ngalau Quarry, near Indarung, McCarthy et al. (2001) collected samples from a 15 m section of bedded chert for radiolarian determination. In the Karang Putih Quarry, 1 km to the south of Indarung, excavated in an isolated hill for the manufacture of cement, lenses of chert are associated with massive limestone. McCarthy et al. (2001) report that the limestone in this quarry is completely recrystallised, possibly due to the effects of a granitic intrusion which occurs a short distance to the south (Fig. 5). They suggest that relationships between limestone and chert in this quarry are tectonic. In an interpretative cross section they show the cherts and limestones imbricated together along low angle thrusts (McCarthy et al., 2001).

Rock units in the Indarung area are well dated from fossil and radiometric age determinations. Radiolarians from chert in the Ngalau Quarry belong to the Transshusum hisukoyense Zone, of Aalenian, early Middle Jurassic age (McCarthy et al., 2001). Lithologies and fossil content of the limestones in the Lubuk Peraku section and in the Ngalau and Karang Putih quarries were described by Yancey and Alif (1977). The limestones are biosparites, with abundant bioclasts, oolitic calcarenites and micrites.
Molluscan shell fragments, pellets, calcareous algae, stromatoporoids and scleractinian corals are common components of the limestones. Among the fossils identified were the (?) stromatoporoids Actostroma and Lovćenipora. The former is considered to be restricted to the Late Jurassic, while the latter is diagnostic of the Late Jurassic to Early Cretaceous. A K/Ar age date of 105 ± 3 Ma (Albian, mid-Cretaceous) is reported from the Golok Tuff in the Lubuk Peraku by Koning and Aulia (1985, from a Caltex Pacific Indonesia internal report).

Pillow lavas and cherts of the Indarung Formation have been equated with the oceanic assemblage of the Woyla Group of Aceh and with the Belok Gadang Formation of the Natal area (Cameron et al., 1980; Rock et al., 1983). Where these rocks are imbricated, deformed and altered to greenschists they may be interpreted, as is the case in Aceh and Natal, as materials accreted from a subducted ocean floor. The recent recognition of Middle Jurassic radiolaria in the cherts (McCarthy et al., 2001) shows that part of this ocean floor was of Jurassic age. The volcanic breccias tuffs and volcanoclastic sandstones of the Indarung Formation are interpreted as the products of seamount volcanism, and the massive limestone with its Late Jurassic–Early Cretaceous fossil fauna is interpreted as part of a fringing reef formed around the seamount (McCarthy et al., 2001). During subduction the seamount with its carbonate cap collided with already accreted ocean floor materials, and the whole assemblage was imbricated to form the present complex.

4.2. Siguntur formation

Mesozoic rocks of the Siguntur Formation are exposed in the Sungai Siguntur, 15 km to the south of Indarung (Fig. 5). The area of outcrop is shown on the Painan Quadrangle Sheet and the lithology is described in the Explanatory Note (Rosidi et al., 1976). Rock types are quartzites, siltstones and shales, the latter sometimes altered to slates, and compact limestones. The map shows that the strike of the beds is E–W, transverse to the general Sumatran trend. In the report the rocks are described as not intensely deformed or folded, but sandstones interbedded with slates showing bedding-parallel cleavage, suggest that the rocks are more highly deformed than first appears. The limestones are reported to contain Lovćenipora, and are therefore of a
similar age to the limestones at Indarung. However, abundant terrigenous quartz in the clastic sediments, notably absent from the Woyla Group in Natal and the rock units at Indarung, suggests that the sediments of the Siguntur Formation had a continental provenance and were deposited in a continental margin environment.

Although these rocks are deformed, with the development of slaty cleavage, there is no suggestion in the descriptions that these rocks have been imbricated or can be interpreted as part of an accretionary complex (Rosidi et al., 1976). In the Siguntur Formation we are dealing for the first time in this account with continentally-derived sediments which were deposited on the Sundaland continental margin.

4.3. Suilak, Tabir, Asai, Peneta and Rawas formations in central Sumatra

Further outcrops of Mesozoic sedimentary and volcanic rocks occur at Suilak 150 km to the southeast of Padang (Fig. 1), in a fault block caught between strands of the Sumatran Fault (Rosidi et al., 1976). These sediments are calcareous siltstones, calcareous shales and limestones. The shales and siltstones are carbonaceous and contain angular...
quartz clasts. The limestones contain *Loftulisa* and *Hydrocorallinae* of Cretaceous age (Tobler, 1922, reported in Rosidi et al., 1976). The volcanic rocks are altered andesites, dacites and bedded tuffs with clasts of augite, hornblende, chlorite and glass. These rocks are the product of Andean arc volcanism on the margin of Sundaland.

Sixty kilometers to the east of Siulak and to the northeast of the Sumatran Fault Zone, in the Batang Tabir, are outcrops of red conglomerates, sandstones and tuffs of the Tabir Formation. Clasts in the conglomerates include quartzite, and andesitic fragments derived from the adjacent Palaeozoic rocks. The presence of *Ostrea* is taken to indicate a Mesozoic, possibly Jurassic age (Tobler, 1922, reported in Rosidi et al., 1976). Continuous with these outcrops and extending southeastwards to the south of Bangko, and also to the northeast of the Sumatran Fault, are large outcrops of Mesozoic rocks of the Asai, Peneta and Rawas formations (Kusnama et al., 1993; Suwarna et al., 1994), (Fig. 1). Rock types include quartz sandstones, siltstones, shales, limestones and tuffs. The Rawas Formation also includes andesite-basalt lava flows, tuffs and volcaniclastic sandstones. Clasts in conglomeratic units in these sediments are derived from the local Palaeozoic basement. Sandstone units show turbiditic characteristics. Argillaceous units have a slaty cleavage striking NW–SE. Fossils, including corals and ammonites, especially from the limestone members, show that these sediments range in age from Middle Jurassic to Early Cretaceous (Suwarna et al., 1994). All these sediments, although subject to later deformation, were evidently deposited in situ on the Sundaland continental basement. Pulunggono and Cameron (1984) suggested that these units were deposited in a foreland basin, but a forearc environment, related to an Andean volcanic arc represented by the volcanics lava flows and tuffs in the Rawas and Tabir Formation is more probable.

### 4.4. Gumai Mountains

Pre-Tertiary rocks form an inlier to the northeast of the Sumatran Fault Zone in the Gumai Mountains of South Sumatra, where they occupy the core of an anticline, surrounded by Tertiary sediments and volcanics (Fig. 7). These Pre-Tertiary rocks are described as the Saling, Lingsing and Sepintiang formations (Gafoer et al., 1992).

Pre-Tertiary rocks form an inlier to the northeast of the Sumatran Fault Zone in the Gumai Mountains of South Sumatra, where they occupy the core of an anticline, surrounded by Tertiary sediments and volcanics (Fig. 7). These Pre-Tertiary rocks are described as the Saling, Lingsing and Sepintiang formations (Gafoer et al., 1992).

The Saling Formation, which forms the northern part of the inlier, is composed of amygdaloidal and porphyritic andesitic and basaltic lavas, breccias and tuffs. The lavas are cut by diorite dykes, regarded as contemporaneous with the lavas, and dated at 116 ± 3 Ma (Early Cretaceous). On the basis of chemical analyses and discriminant plots the
lavae are interpreted as theloites of oceanic affinity (Gafoer et al., 1992). The Lingsing Formation in the southern part of the inlier, contains similar igneous rocks, interbedded with claystone, siltstone, sandstone, calcilutite and chert. The Saling and Lingsing formations are therefore considered to be contemporaneous. Since the tholeiitic basalts are associated with serpentinised ultrabasic pyroxenites and cherts, the whole assemblage is regarded as ophiolitic sequence of ocean floor origin. Although the rocks are highly deformed and folded it is not clear from the descriptions whether they are imbricated to form an accretionary complex (Gafoer et al., 1992). The strike of bedding and cleavage in the sediments is said to be N–S. The the mapped E–W contact between the Saling and the Lingsing formations is therefore presumably tectonic (Fig. 7).

The Saling and Lingsing formations are overlain discordantly by the Sepintiang Limestone Formation (Fig. 7). This is composed of massive, brecciated and bedded limestones, containing the coral Calamophylliposis crassa (Late Jurassic), the foraminifera Pseudotextulariella, small Cuneolina (Early Cretaceous) and Orbitolina sp. (mid-Cretaceous). The contact between the Sepintiang Limestone and the underlying units is considered to be tectonic (Gafoer et al., 1992).

All of these units are cut by granitic intrusions, which by analogy with similar dated granitoids further south in the Garba Mountains, are regarded as of Late Cretaceous age (Gafoer et al., 1992). The rocks of the inlier and the surrounding Tertiary rocks are also cut by NW–SE trending faults, some showing strike-slip displacements (Fig. 7), and are evidently related to the Sumatran Fault System, the main strands of which lie some 25 km to the southwest.

As already noted, Gafoer et al. (1992) interpreted the igneous rocks of the Saling Formation as ocean floor basalts, on the basis of their tholeiitic composition and their association in the field with serpentinites and cherts. However, the presence of andesites, the amygdaloidal and porphyritic textures, together with association of the volcanics with the massive Sepintiang Limestone, suggest that the Saling Formation also includes part of a volcanic arc. The description of the Saling Formation closely resembles that of the Bentaro Volcanic Formation of Aceh (Bennett et al., 1981a) and the Nabana Volcanic and Parlungpang units of the Batang Natal (Wajzer et al., 1991). The Early Cretaceous age shows that the Saling Volcanic Arc was active contemporaneously with the Bentaro Arc of Aceh.

The Sepintiang Limestone may be interpreted in the same way as the limestones in Aceh, as a fringing reef surrounding a volcanic arc. Fossil evidence of the Late Jurassic to mid-Cretaceous age of the Sepintiang Limestone Formation means that it can be correlated directly with the Lamno, Teunom and Sise Limestone formations of Aceh (Bennett et al., 1981a; Cameron et al., 1983), the Batu Nabontar limestones in the Batang Natal section (Wajzer et al., 1991) and the Lubuk Peraku limestones at Indarung (Yancey and Alif, 1977).

The Lingsing Formation, composed of siltstones, shales and cherts, has been interpreted as deposited in a bathyal environment (van Bemmelen, 1949; Gafoer et al., 1992). The presence of lavas interbedded with clastic deposits, suggests that the Lingsing Formation represents more distal flows, volcaniclastic sediments and clastic carbonates derived from the arc extending out onto an ocean floor, represented by the bedded cherts. These rocks resemble clastic units in the Lho'nga Formation of Aceh (Bennett et al., 1981a) and the Belok Gadang Siltstone and Rantobi Sandstone formations of Natal (Wajzer et al., 1991).

4.5. Garba Mountains

The Garba Mountains form an inlier of pre-Tertiary rocks, about 100 km to the southeast of the Gumai Mountains and also northeast of the Sumatran Fault Zone (Fig. 1). The inlier is shown on the GRDC Baturaja Quadrangle Sheet (Gafoer et al., 1994) (Fig. 8). The oldest unit, which outcrops on both eastern and western sides of the inlier, is the Tarap Formation, composed of phyllite, schist, slate, minor quartzite and marble, metamorphosed in the greenschist facies. The age of the Tarap Formation is unknown, but it is presumed to be older than the adjacent, but unmetamorphosed Garba Formation, and is interpreted as the metamorphosed Palaeozoic basement of Sumatra (Gafoer et al., 1994). Outcrops of the Tarap Formation occur within the Garba Formation and in large areas to the east and west. The relationships between the metamorphic Tarap Formation and the Garba Formation, as shown on the map, are not clear (Gafoer et al., 1994) (Fig. 8). The eastern contacts are faulted and possibly thrust. If the Tarap is part of the metamorphosed Palaeozoic basement of Sumatra, it may represent the western margin of the Sundaland continent, thrust westwards over accreted ocean floor materials represented by the other units in the inlier. The present distribution of these metamorphic rocks could be due to the disruption of the thrust sheet by faulting and erosion.

The Garba Formation consists of (?)amygdaloidal and porphyritic basaltic and andesitic lavas, associated with sheared serpentinite and lenses and intercalations of radiolarian chert. An Insu Member is distinguished on the map, with a similar lithological assemblage, but also containing interlayered lenticular bodies of mélangé, with boulders of basalt, andesite, radiolarian chert, claystone, siltstone, schist and massive limestone in a scaly clay matrix (Gafoer et al., 1994). The limestones found as blocks do not outcrop elsewhere in the inlier, but are presumed to be derived from an unexposed component of the Garba Formation. Blocks of the Tarap metamorphics are notably absent from the mélangé. The foliation in the scaly matrix and the elongation of the enclosed blocks, which are cut by tension fractures normal to their long axes, trends in a NW–SE direction (Gafoer et al., 1994). A fault-bounded sliver on the eastern side of the inlier, and a few other scattered outcrops where chert is abundant, are mapped as the Situlanglang Member.
Two fold phases are recognised in the Garba Formation, an earlier phase of E–W folds and a later phase of NE–SW folds (Gafoer et al., 1994). Neither the cherts nor the limestones have so far yielded age-diagnostic fossils.

Both the Tarap and the Garba formations are intruded by the Garba Pluton, a composite body in which an older component has been dated at $115 \pm 4$ and $102 \pm 3$ Ma (mid-Cretaceous) and a younger component at $79 \pm 1.3$ and $89.3 \pm 1.7$ Ma (Late Cretaceous). Rock units within the inlier are cut and bounded by NW–SE trending faults. Although these faults are parallel to the Sumatran Fault System they do not appear to affect significantly the Tertiary rocks and must be largely of Pre-Tertiary age.

The Garba Formation has been compared to the Woyla Group of Natal (Gafoer et al., 1994) and certainly lithological descriptions of this formation and its Insu and Situlanglang members, correspond very well with those from Aceh and the Batang Natal section. The basaltic and andesitic lavas of the Garba Formation correspond with those of the Bentaro Arc, and may similarly be interpreted as part of a volcanic arc sequence. Limestone blocks within the mélange may represent fragments of fringing reefs or the collapsed carbonate cappings of seamounts, the latter now represented by volcanics in the Garba Formation, as has been suggested for the Natal and Indarung areas (Wajzer et al. 1991; McCarthy et al., 2001). Descriptions of the mélanges of the Insu Member of the Garba Formation (Gafoer et al., 1994) are identical to those from Natal (Wajzer et al., 1991). The interlayering of the Insu Member with lavas, chert and mélange (Gafoer et al., 1994) suggests that these rocks are deformed and imbricated in the same way as the Woyla Group in the Batang Natal section, and similarly represent an accretionary complex formed by subduction of an ocean floor. It may be that some of the low grade metamorphic schists mapped within the Insu Member as Tarap Formation, are part of this accretionary complex, as metamorphic rocks, up to greenstone facies, are incorporated in the accretionary complex at Natal.

The mid- to Late Cretaceous Garba Pluton (115–79 Ma) intrudes both the Tarap and the Garba formations, so that the accretion of the Garba Formation to the margin of Sunda-land, if the Tarap is correctly identified as Palaeozoic basement, took place before the mid-Cretaceous. The age of the younger component of the Garba Pluton is comparable to that of the Sikuleh Batholith in Aceh (98 Ma) and the Manunggal Batholith (87 Ma) in Natal.
4.6. Bandarlampung area

Pre-Tertiary rocks occur as scattered outcrops among Tertiary and Quaternary volcanic and volcaniclastic sediments in the area between Kotaagung and Bandarlampung in Lampung Province, southern Sumatra (Amin et al., 1994; Andi Mangga et al., 1994) (Fig. 9). Outcrops towards the northeast of the area consist of pelitic, calcareous, quartzose or graphitic schists and sericitic quartzites, with intercalated gneiss, marble and amphibolites, described as the Gunungkasih Complex. Within the complex there is a tendency for outcrops to the northeast to be composed of orthogneiss, while those to the southwest are composed of metasediments. The strike of the foliation in the schists trends generally NW–SE but the schistosity is folded about E–W axes and refolded by NW–SE trending upright folds and then by variably oriented kink band folds. These rocks are suggested to be equivalent to the Tarap Formation of Garba and metamorphic equivalents of the Palaeozoic Tapanuli Group in Aceh and the Kuantan Formation in the Padang area (Amin et al., 1994; Andi Mangga et al., 1994).

Outcrops of unmetamorphosed rocks, identified as the Menanga Formation, lie largely to the southwest of the Gunungkasih Complex (Fig. 9). These consist of tuffaceous and calcareous claystones, sandstones and shales with intercalated radiolarian-bearing cherts, manganese nodules and coral limestones and rare porphyritic basalt. The sandstones contain clasts of glassy andesite and lithic fragments of andesite, quartz-diorite and quartzite. The cherts have not so far yielded diagnostic radiolarians, but Zwierzycki (1932, confirmed in Andi Mangga et al., 1994), reports the occurrence of *Orbitolina* sp. of Aptian-Albian (mid-Cretaceous) age from limestones in the Menanga river section. The bedding strikes NW–SE with dips of 35°–60° to the northeast. The rocks are folded and cut by faults, with slickensides indicating reverse movement.

The contact between the Gunungkasih Complex and the Menanga Formation in Gunung Kasih is obscured, due to rice cultivation, and in Teluk Ratai is at present inaccessible as it lies within a Naval Base (Fig. 9). However, the latter contact in the Menanga River was described by Zwierzycki (1932) as occupied by a ‘friction breccia’. On the GRDC maps Amin et al. (1994) and Andi Mangga et al. (1994) show both these contacts as thrusts (Fig. 9).

The Menanga Formation is interpreted by Amin et al. (1994) as a deep water marine sequence with interbedded...
basalt lavas and andesitic clastic fragments, derived from a volcanic arc, and deposited in a trench or forearc environment. These sediments were deformed during accretion to the Sumatran margin, represented by the Gunungkasih Complex. K/Ar radiometric ages, ranging from 125–108 Ma (mid-Cretaceous) from hornblende in an amphibolitic schist in the Menanga Formation, is taken as the age of accretion (Andi Mangga et al., 1994). However, the presence of quartzite and quartz-diorite clasts suggests that the Menanga Formation was, like the Rawas and associated formations in central Sumatra, derived from an Andean arc built on a continental basement, and was deposited in a forearc environment. The Menanga Formation was overthrust by the basement at a later stage.

Near Bandarlampung, spectacular exposures of the Gunungkasih Complex are intruded by the Sulan Pluton (Fig. 9). The pluton is a composite body which includes gabbro, dated by K/Ar radiometric analysis at 151 ± 4 Ma (Late Jurassic), hornblende and biotite granites and granodiorite intruded by late aplogranite dykes. Granite from the Sulan Pluton gave an age of 113 ± 3 Ma (mid-Cretaceous) (McCourt et al., 1996).

To the north of Bandarlampung, spectacular exposures below an irrigation dam on the Sekampung River show extensive outcrops of granodioritic and dioritic gneiss, containing basic xenoliths, and cut by discordant granitic and pegmatitic veins. The granitic and granodioritic gneisses are cut by basaltic dykes, several metres thick, which contain xenoliths of gneiss. The gneiss xenoliths show evidence of melting, and towards the margins of the dykes are drawn out into streaks, which are sometimes isoclinally folded, parallel to the dyke margins. The dykes and the foliation in the gneisses both trend in a NW–SE direction. Fold structures in the dykes and the curvature of foliation in the gneisses indicate that the dyke margins have acted as strike-slip shear zones, with a sinistral sense of movement. Sub-horizontal slicksides on foliation surfaces within the gneiss indicate the same sense of movement. Diorite from the Sekumpang exposure has been dated by the K/Ar method at 89 ± 3 Ma (late mid-Cretaceous) (McCourt et al., 1996).

In the same area, in the Wai Triplek, greenschist facies white mica-quartz schists are intruded by metadolerite dykes. The margins of the dykes show compositional banding which is isoclinally folded, in a similar fashion to the dykes in the Sekampung River. Further upstream the bed of the Wai Triplek exposes streaky acid and basic gneisses cut by more homogeneous basic dykes. Acid gneiss shows evidence of having been melted and recrystallised along the dyke contacts, and quartz-feldspar veins fill fractures in brecciated basic dyke material, in a process of back injection.

Relics of dyke rocks occurring as basic xenoliths in gneiss, and gneiss xenoliths enclosed in in basalt dykes, indicate that the intrusion of basaltic dykes and granitic bodies alternated during the development of the gneiss complex at Sekampung. Exposures in the Wai Triplek form part of the same gneiss complex, but also contain fragments of the schistose continental basement into which the igneous rocks were intruded. During or shortly after intrusion, both granitic and basic rocks were affected by sinistral shearing, which converted the granitic and dioritic rocks into gneisses and deformed the basic dykes. The alternation of acid and basic intrusion, with contemporaneous deformation, are characteristic features of the basal parts of a magmatic arc, where acid and basic magmas are intruded into an active strike-slip fault zone. This situation is similar to that which exists beneath Sumatra at the present day where the modern volcanic arc is built on the active Sumatran Fault Zone. However, the sense of movement along the present arc is dextral, in the opposite sense to the sinistral movement along the Cretaceous arc.

5. Tectonic evolution of the Sundaland margin

5.1. Pre-Cretaceous Sundaland Continent

The concept that Southeast Asia, and indeed Asia as a whole, has been built up during the Phanerozoic by the amalgamation of allochthonous terranes derived from the northern margin of East Gondwanaland, is now well established in the literature (e.g. Metcalfe, 1996 and references therein). In Metcalfe’s (1996) version of the concept a series of elongated terranes separated successively from the North Gondwanaland margin by the development of ocean basins behind them. These oceans are referred to as Palaeo-Tethys, Meso-Tethys and Ceno-Tethys. The Indochina Block which forms the core of Southeast Asia had separated from Gondwanaland by Late Devonian times and amalgamated with the South China Block by the Early Carboniferous. To this core was added the Shan-Thai or Sibumasu Block, which separated from Gondwanaland in the Permian and amalgamated with the Indochina Block in the Late Permian or Triassic (Metcalfe, 1996).

Following the completion of the Integrated Geological Survey of Northern Sumatra, these concepts were extended by Aspden et al. (1982) and Pulunggono and Cameron (1984) to interpret the structural evolution of the southwestern margin of Sundaland in Sumatra. The model was later extended to cover southern Sumatra (McCourt et al., 1993). The interpretation of the structure of Sumatra illustrated in Fig. 10 is adapted from the Tectonic Map of Northern Sumatra (Aspden et al., 1982). In this map Sumatra is shown with its present NW–SE orientation, but several reconstructions, including those by Metcalfe (1996), show Sumatra with an E–W orientation during the Mesozoic. The Indochina Block is represented by the East Malaya Microplate, occupying the eastern part of the Malay Peninsula and sutured to the Malaccan Microplate along the Raub-Bentong Line. To the west the Malaccan Microplate is joined by the Mergui Microplate along a Triassic suture known as the Mutus Assemblage, identified only from the occurrence of
mauve shales, cherts, volcanic rocks, gabbros and serpentinites in oil company boreholes (Eubank and Makki, 1981; Pulunggono, 1983).

In northern Sumatra the Mergui Microplate is made up of the Permo-Carboniferous Tapanuli Group, including the Bohorok Formation, composed of 'pebbly mudstones', interpreted as glacio-marine sediments, and correlated with the Singha Group in the Langkawi Islands and the Phuket Group of western Thailand (Cameron et al., 1980). Southwards, these rocks are recognised in the Tigapuluh hills of central Sumatra (Simandjuntak et al., 1991; Suwarna et al., 1991). It is also suggested that the Gunungkasih Complex of the Bandarlampung area may represent the extension of the metamorphosed representatives of the Tapanuli Group into southern Sumatra (McCourt et al., 1993; Amin et al., 1994; Andi Mangga et al., 1994). A Permian volcanic arc was added to the southwestern margin of these amalgamated terranes in the Triassic (McCourt et al., 1996).

Fig. 10. The structure of the southwestern margin of Sundaland (with its present orientation) in Late Cretaceous times, according to the interpretation given in the paper. Note that the effects of post-Middle Miocene movements along the Sumatran Fault Zone have been removed. Data from sources quoted in the text.

5.2. The Late Mesozoic Continental Margin

In their review of Mesozoic to Cenozoic plutonism in Sumatra, McCourt et al. (1996) identify a belt of Middle Jurassic to Early Cretaceous intrusions, including the Sulit Air suite (203 ± 6 Ma) and the Bungo Batholith (169 ± 5 Ma), adjacent to the suture between the Mergui Microplate and the Permian Volcanic arc. These plutons are subduction-related, I-type granites formed by the northeasterly subduction of an oceanic plate which lay off the continental margin of Sundaland, to the southwest (Fig. 11A). Remnants of the volcanic rocks related to this phase of magmatism may be represented by andesitic and basaltic volcanic rocks in the Rawas, Tabir and Siulak formations of central Sumatra and by tuffs in the Menanga Formation of southern Sumatra. However, there is no evidence that this arc extended into northern Sumatra.

This magmatic arc assemblage is termed the Rawas Arc in the reconstruction illustrated in Fig. 11A. Associated deep-water turbiditic sandstones, shales and the shallow-water fossiliferous limestones of the Rawas, Asai, Peneta and Menanga formations, well-dated by fossil evidence and ranging in age from mid-Jurassic to Early Cretaceous, were contemporaneous with the magmatic arc, and can be interpreted as forearc basin deposits (Fig. 11A). Further to the
northwest, clastic sediments of the Tabir, Siulak and Siguntur formations which contain both volcanic and continentally-derived clasts, may also have been deposited in this same forearc basin.

Oceanic crustal material and slices of mantle, remnants of the oceanic plate which was being subducted off the southwestern margin of Sundaland at this time and incorporated into an accretionary complex, now form the ‘oceanic assemblage’ of the Woyla Group. As described in this account, units composed of ocean floor components, and correlated with the Woyla Group, have been recognised all along the west coast of Sumatra, from Banda Aceh to the Garba Mountains. The continental margin against which accretion took place can be recognised in Aceh, where rocks of the Tapanuli and Peusangan groups, representing the Mergui Microplate and the Permian Volcanic arc, are thrust over the Woyla Group along the Kla and Takengon lines.

The age of the ocean floor which was being subducted is indicated only by fragmentary evidence, but a Late Triassic age is indicated by foraminifera in a limestone block in the Batang Natal section, interpreted as a seamount capping (Wajzer et al., 1991) and by mid-Jurassic radiolaria in chert from Indarung (McCarthy et al. 2001). Abundant fossil evidence from Late Jurassic–Early Cretaceous faunas in limestones correlated with the Woyla Group, from Aceh to the Gumai Mountains, show that the ocean with seamount caps or fringing reefs continued to exist throughout these periods. The youngest fossils, found in units correlated with the Woyla Group, are the Aptian-Albian foram *Orbitalina* which occurs in the Menanga Formation near Bandar lampung and the Sepringtiang Limestone Formation of the Gumai Mountains. Evidently the last remnants of the Woyla Ocean were subducted late in mid-Cretaceous times. This segment of ocean floor can be identified as part of the Meso-Tethys, which lay to the north of India before that continent separated from Gondwanaland (Metcalfe, 1996).

### 5.3. Bentaro-Saling Volcanic Arc

Basaltic and andesitic volcanic rocks, agglomerates, tuffs and volcanioclastic sediments correlated with the Woyla Group occur throughout the western part of Sumatra, from Banda Aceh to the Gumai Mountains. These units include the Bentaro and Tapaktuan Volcanic formations in Aceh, the Tambak Baru and Parlumpungan units in Natal, the Saling Formation in the Gumai Mountains and the Garba Formation in the Garba Mountains. At Bentaro near Banda Aceh these rocks occur as vents surrounded by breccias, tuffs and volcanioclastics and intruded by basic dykes. The lavas are often amygdaloidal and porphyritic and are closely associated in the field with massive or bedded limestones.

Limestone units include the Lho’nga, Raba, Lamno, Lhoong and Teunom Limestone formations of Aceh, the Batu Nabontar Limestone Unit of Natal, the Lubuk Peraku and Karang Putih limestone formations of Indarung and the Sepringtiang Limestone Formation of the Gumai Mountains.
The limestones commonly contain volcanic clasts, especially in basal units, and may be interbedded with volcaniclastic deposits. No direct age for the volcanism has yet been obtained from the volcanic rocks themselves but, as detailed in this account, the limestone units have sometimes proved abundantly fossiliferous and contain a wide range of fossil groups, indicating ages ranging from Late Jurassic to Early Cretaceous. Cameron et al. (1980) interpreted the intrusive and extrusive volcanic rocks in Aceh as the remnants of a Late Jurassic to Early Cretaceous volcanic arc, emergent above sea level where it was eroded to form breccias and volcaniclastic sediments. The arc was surrounded and overlain by fringing reefs represented by the massive limestones. In this model, limestones were eroded to form breccias, passing into bedded detrital limestones in deeper water. This interpretation may be extended to all the other occurrences of these rock units in Sumatra which have been correlated with the Woyla Group (Fig. 11).

The Bentaro-Saling Volcanic Arc collided with the margin of Sundaland when the last fragment of the subducting 'Woyla' (Meso-Tethys) ocean was incorporated into the accretionary complex in the late mid-Cretaceous. The site of the collision is marked in Aceh by the Geungpang Line where the 'oceanic assemblage', forming an accretionary complex, is thrust over the rocks of the arc and its fringing reefs (Figs. 10, 11B). The collision had repercussions further back on the continental margin where Palaeozoic basement rocks of the Megui Microplate were thrust over the eastern margin of the Asai-Rawas-Peneta Forearc Basin, accounting for the deformation with the development of folds and slaty cleavage in the agillaceous units which is seen in these formations, and also in the Siguntur Formation near Padang (Fig. 11B).

5.4. Late Cretaceous continental margin

With the accretion of the Bentaro-Saling Arc to the southwestern margin of Sundaland, subduction of the oceanic plate continued outboard of the new margin. This situation is illustrated in Fig. 10 in which the arc terrane and the Woyla accretionary complex are returned to their original position along the Sundaland margin by reversing the post-Miocene dextral movements along the Sumatran Fault system. On Sundaland, the development of a Late Cretaceous magmatic arc, represented by granitoid intrusions from Aceh to Bandarlampung, provides evidence for continued subduction outboard of the accreted terranes. All these granitoid intrusions are of I-type and were intruded through continental crust (McCourt et al., 1996). The Late Cretaceous arc lies oceanward of the preceding mid-Jurassic to Early Cretaceous arc, and is largely intruded through the recently accreted oceanic material and the newly accreted volcanic arc of the Woyla Group and its equivalents (Fig. 11B). In Aceh the Sikuleh Batholith (97 Ma) is intruded into the Bentaro Arc, in Natal the Manunggal (87 Ma) and Kanaikan batholiths are intruded into the oceanic assemblage, including mantle peridotite, of the Woyla Group. In the Gumai and Garba Mountains the accreted oceanic assemblage and the arc rocks are now situated to the north-east of the Sumatran Fault Zone. In Gumai granitic rocks are intruded into the Saling Formation of the arc assemblage and in the Garba Mountains the Garba Pluton (115–90 Ma) is intruded into both arc and oceanic material and also into the Tarap Formation, regarded as metamorphosed Palaeozoic of the Mergui Plate (Gafoer et al., 1994). In Bandarlampung the Sulan Pluton (113 Ma) and the Sekampung Complex (89 Ma) are intruded into the Gunungkasih Complex, again interpreted as Palaeozoic basement rocks of the Mergui Plate (Amin et al., 1994; Andi Mangga et al., 1994).

As has been described in this account, detailed observations in the Sekampung Gneiss Complex provide evidence that granitic and basic rocks of the Late Cretaceous arc were intruded into an active shear zone, suggesting that the Late Cretaceous arc, like the present arc, was developed during a phase of oblique subduction and was intruded into an active transcurrent fault system. Reports of ‘flow foliation’ in the Sikuleh Batholith (Bennett et al., 1981b) and of gneissose rocks in other Late Cretaceous plutons, may also have the same significance. Kinematic indicators at Sekampung show that this transcurrent fault system operated in a sinistral sense, in the opposite sense to the present system. This interpretation is shown on Figs. 10 and 11B.

6. Conclusions

The concept of the Woyla terranes can now be reconsidered in the light of the evidence which has been reviewed in this account, and in the context of the tectonic model for the evolution of the southwestern continental margin of Sundaland during the Late Mesozoic which has been derived from this evidence and presented above.

6.1. Natal terrane

The Natal terrane was identified Rock et al. (1983) and interpreted by analogy with the Sikuleh terrane of Aceh (Cameron et al., 1980). In Rock et al.’s (1983) interpretation the Natal terrane was composed of the Langsat Volcanics, of unusual chemical composition (K-rich absarokites), and the contemporaneous volcaniclastic turbidites of the Sikubu Formation at the southwestern end of the Natal river section. Rock et al. (1983) argued that, since the volcanics are intruded by the Air Bangis granites, they must be underlain by continental crust and constitute a microcontinental block. However, age-dating of the Langsat Volcanics (Wajzer et al., 1991) showed that the volcanics were of Late Eocene age, and therefore unrelated to the Triassic–Early Cretaceous Woyla Group, which forms the remainder of the section, and therefore also quite unrelated to the Late Jurassic–Early Cretaceous Bentaro Volcanics of Aceh.

The Langsat Formation is separated from the Woyla
Group by the Simpang Gambir Fault (Figs. 3 and 4) which is parallel to, and presumably part of the main Sumatran Fault System. It is probable that these volcanic rocks have been moved into their present position by movements along the fault, from a position further south along the west Sumatran margin. In this respect they constitute an allochthonous terrane.

Although the Langsat Volcanics have a unique composition, not identified elsewhere in Sumatra, they may have moved no great distance. Oligo-Miocene volcanic units of basaltic to andesitic composition are found all along the west coast of Sumatra. In Breueh Island, to the north of Banda Aceh, Oligocene volcanic rocks of basaltic to andesitic composition, with subaerial pyroclastics, have shown by palaeomagnetic measurements that they were extruded at 4° of latitude, ~400 km to the south of their present position (i.e. near Sibolga), and must have been translated along the Sumatran Fault System to their present position since Oligocene times (Haile, 1979). This interpretation is compatible with regional considerations, which indicate that movements along the Sumatran Fault, related to the spreading ridge in the Andaman Sea, reduce southwards, from 460 km in the north, to virtually nothing in the Sunda Strait to the south (Curry, 1989; McCaffrey, 1991). In this model the Langsat Volcanics are likely to have originated some 200 km to the south of their present position.

Volcanic rocks of Eocene–Oligocene age extend all along the west coast of Sumatra to the south of Natal. These were designated the ‘Old-Andesites’ by van Bemmelen (1949) and include the Oligo-Miocene Painan Volcanic Formation of andesitic to dacitic composition, with ignimbrites and acid tuffs, outcropping along the coast to the south of Padang; the (?) Eocene Bandan Volcanic Formation, composed of ignimbrites, andesites and tuffs, which overlies the Mesozoic inlier at Silulak; and the (?) Palaeocene–Eocene Kikim Volcanic Formation, composed of andesitic breccias and welded tuffs interbedded with quartzose sediments, overlying Mesozoic rocks in the Gumai and Garba mountains of South Sumatra. Eocene–Oligocene ‘Old-Andesites’ also occur along the south coast of Java (van Bemmelen, 1949).

None of these other volcanic units resemble the Langsat Volcanic Formation, either petrographically or geochronologically, but this may be because the latter shows only limited exposure. Rock et al. (1983) emphasised that both the composition and the position of the Langsat Volcanics are anomalous. K-rich absarokites, are characteristic of a back-arc tectonic environment. Presumably, the volcanic arc to which these rocks are related is developed much more extensively to the west, but is now buried beneath younger Tertiary deposits in the forearc basin. Rock et al. (1983) point out that the position of the Langsat Volcanics on the west coast of Sumatra, well to the west of the present day volcanic arc in the Barisan Mountains, is also anomalous. As also is the position of the younger Miocene volcanic arc, which lies on the western side of the Barisans, again to the west of the present arc. In a continuously subducting subduction system it would be expected that younger arcs would lie progressively oceanward (southwestward in the Sumatran arcs) of older arcs. This is clearly not the case in Sumatra. One possible explanation is that extensive areas of the forearc have been carried away along strike-slip faults, parallel to the Sumatran Fault System as the result of oblique subduction. The present position of these slices of forearc should now be sought further to the northwest, in the Andaman Sea or in the Arakan Ranges of Burma. However, there is no basis for suggesting that the Langsat Volcanics are entirely allochthonous to western Sumatra.

6.2. Sikuleh terrane

The concept of the Sikuleh terrane and the marginal sea model for its origin were developed by Cameron et al. (1980) to account for the occurrence of the imbricated Woyla oceanic assemblage between the Bentaro Volcanic Arc, regarded as overlying a fragment of Sumatran continental crust, and the remainder of Sumatra. Evidence for the presence of a continental fragment beneath the arc includes: the intrusive Sikuleh Batholith; components of the Sumatran basement among arc rocks; and tin anomalies associated with the granite. All of these observations are open to question.

The presence of the Sikuleh Batholith, by itself, does not constitute conclusive evidence that the Bentaro volcanic arc is underlain by continental crust. The batholith is a composite body, including gabbroic, dioritic and granodioritic components, with little or no true granite, in which later intrusions cut earlier, and the older components are gneissose. These are the characteristics of a subduction-related, mantle-derived, I-type granitoid body, forming part of a magmatic arc, which was intruded into an active transcurrent fault zone. The detailed petrography and geochemistry of the batholith need to be the subject of future studies to determine the origin of the components of the igneous body and to determine whether it was intruded through continental crust.

The argument for a separated sliver of continental basement to the Bentaro Volcanic Arc is considerably strengthened by the occurrence of the ‘undifferentiated’ Woyla Group rocks along the southern contact and as roof pendants within the Sikuleh Batholith. These rocks are described as resembling metasediments of the Carboniferous Kluet Formation which constitutes part of the Palaeozoic basement of Sumatra. In the Explanatory Note to the Calang Quadrangle these rocks are described as constituting an ‘inlier’ within the Bentaro Arc rocks (Bennett et al., 1981b), the implication here is that the Kluet underlies the arc rocks, and has been uplifted and exposed by erosion. To the northeast of the Sumatran Fault, however, Palaeozoic basement rocks are thrust over the Woyla Group along the Geumpan, Takengon and Kla lines. It has been suggested in the model presented in this account, following Cameron
et al. (1980), that thrusting occurred during the accretion of the Woyla Group rocks to the Sumatran margin, and prior to the intrusion of the Sikuleh Batholith. A possible alternative explanation to a basement origin for the Kluet rocks is that they formed part of a thrust sheet overlying the Woyla Group, and subsided into the batholith during its intrusion. These possibilities can only be resolved by careful study of the field relationships of these rock units.

A further line of evidence pointing to the presence of continental basement rocks beneath the Bentaro Volcanic Arc are the tin anomalies associated with the Sikuleh Batholith. Tin ores are commonly associated with highly peraluminous granitic rocks concentrated by a process of magmatic differentiation and generally restricted to continental crust. However, there are peculiarities in the occurrence of the tin in Aceh. No primary ore deposits were identified and there are no records of tourmaline or fluorite, associated with tin deposits elsewhere in the world. Nor is there any record of muscovite granites, although both pegmatites and aplites occur in Sikuleh (Bennett et al., 1981b).

Tin anomalies are not restricted to the granite outcrop, but extend southeastwards parallel to the Anu-Batee Fault, across the outcrop of the oceanic assemblage of the Woyla Group (Stephenson et al., 1982). This cannot be a primary relationship, as tin ores have never been found in an oceanic environment. In Sikuleh tin anomalies were identified by the analysis of stream sediment samples. Similar anomalies, associated with peraluminous granites, occur extensively throughout the eastern part of Sumatra to the east of the Sumatran Fault, where they form part of the Thai-Malay tin belt. It is possible that tin, found in stream sediments in Sikuleh and on the Woyla outcrop, was derived from the area to the east of the Sumatran Fault by the erosion of primary tin deposits, or secondarily from basal Tertiary sediments, and transported across the fault.

As detailed above the presence of Kluet metasediments and tin anomalies provide a good case for regarding the Bentaro Volcanic arc as underlain by a detached fragment of the Sumatran continental basement, as proposed by Cameron et al. (1980). On the other hand, the marginal sea hypothesis (Cameron et al., 1980), in which the oceanic assemblage of the Woyla Group is interpreted as the product of a narrow and short-lived ocean basin has been shown to be unlikely. Evidence has been presented in this account which indicates that the Woyla Group represents the remnants of a major ocean basin, lasting from at least Triassic times until the mid-Cretaceous, a time span of more than one hundred million years. This time span coincides with the development of the Meso-Tethys in the plate reconstructions of Metcalfe (1996).

The identification of the Sikuleh and Natal microcontinental fragments as allochthonous terranes (Wajzer et al., 1991) encouraged Metcalfe, in his comprehensive synthesis of the accretion of Southeast Asia, to propose that the Sikuleh and Natal terranes originated on the northern margin of East Gondwanaland off northern Australia, like the other components of Southeast Asia (Metcalfe, 1996). The Eocene–Oligocene age-dating of the Natal terrane excludes it from this scenario. In his synthesis Metcalfe (1996, his Fig. 13), following earlier authors, suggests that a linear continental sliver, which included Sibumasu (Mergui Microplate in Fig. 10), separated from the northern margin of Gondwanaland in the Early Permian with the formation of Meso-Tethys, and was accreted to Southeast Asia by Late Triassic times. He further suggests that a second linear sliver, including West Burma, West Sulawesi and the Sikuleh Microcontinent, separated from Gondwanaland in the Late Jurassic with the formation of Ceno-Tethys (Metcalfe, 1996, his Fig. 15). This second sliver had collided with the southwestern margin of Sundaland by the Late Cretaceous.

Three hypotheses can be proposed for the origin of the Bentaro Volcanic Arc and the Sikuleh terrane: the arc developed on a fragment separated from the Sumatran continental basement as an Andean arc as suggested by Cameron et al. (1980); the arc developed on a continental fragment separated from the northern margin of Gondwanaland during its passage across Tethys and before its collision with Sumatra (cf. Metcalfe, 1996); the arc developed as an intra-oceanic arc built up on the oceanic crust of Meso-Tethys before colliding with Sumatra (Fig. 11). Further studies are required to distinguish between these alternative hypotheses.

Acknowledgements

The author is deeply indebted to the geologists of the Indonesian Directorate of Mineral Resources, the Geological Research and Development Centre, Bandung and the British Geological Survey who gathered the greater part of the data presented in this paper. He is especially grateful to geologists from these organisations who guided him in the field in Sumatra, most recently Nana Suwana and Aang Achdan of GRDC. He has benefited from administrative and logistic support arranged over many years by successive Directors of DMR, GRDC and by Dr Bona Situmorang, previously Head of the Geology Division of Lemigas, Jakarta. Financial support for fieldwork in Sumatra has been provided to the University of London Research Group, by the UK Natural Environment Research Council (NERC) and a Consortium of Oil Companies. The author is also indebted to Ian Metcalfe for inviting this contribution and Nick Cameron for a challenging review of the original draft.

References


