THE STRUCTURE OF EASTERN INDONESIA:

AN APPROACH VIA GRAVITY AND OTHER GEOPHYSICAL METHODS.

A Thesis submitted for the

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PLEASE NOTE THAT THE INTRODUCTORY FIGURES FOLLOW THE ABSTRACT

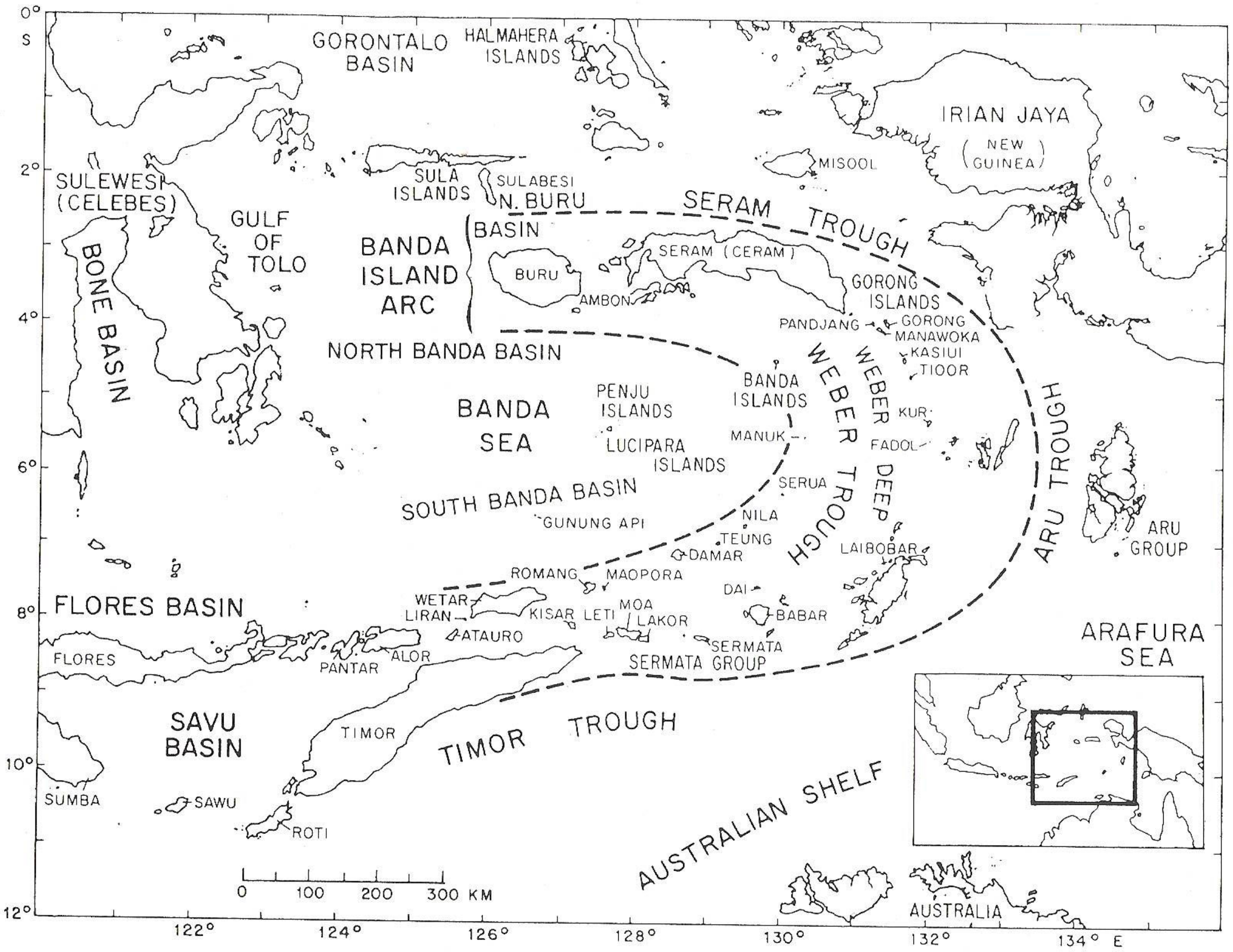
ABSTRACT

Gravity and other geophysical data have been collected, processed and interpreted for the southern Banda Arcs, Eastern Indonesia. Land and marine data, from Timor in the west to the Kai Islands in the east, have been combined to allow examination of the crustal structure and tectonic evolution of the 3M.yr. old collision between the northward migrating Australian Plate and the Banda Sea micro-plate(s).

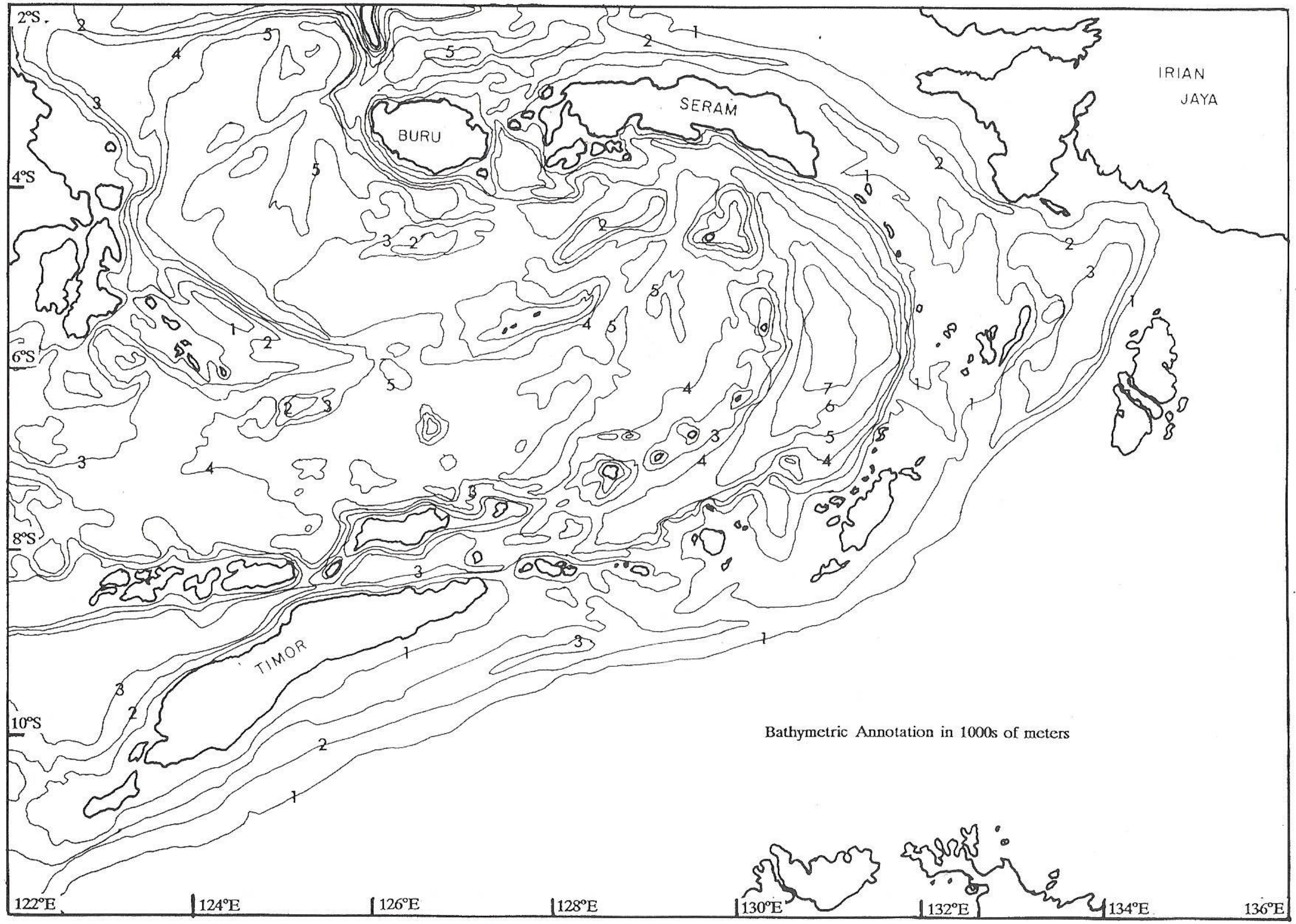
Following collision in the Timor region, approximately 60 km of continental and volcanic margin crust may have been subducted. Further convergence caused the steepening of the Benioff Zone, resulting in the rupturing of the continental margin along new subduction decollements, thereby progressively isolating the continental crustal units in the north of Timor from the later formation of the southern imbricate wedge. Shortening between the inner arc and the suture zone, situated off-shore of north Timor, was possibly by eastward translation of crustal blocks, thickening of the arc and tectonic erosion. Timor was dissected by a number of large left-lateral faults during the collision process giving rise to a number of variably sized, crustal blocks. The same process was, and probably still is, active in the Tanimbar Islands, which has a similar gravity field to Timor. The Kai Islands, to the north of the Tanimbars, are part of a large, displaced, continental crustal block, with a geology similar to Tanimbar and Timor.

The gravity field from Timor around the Banda Arc to Tanimbar has a common Bouguer anomaly profile, with values of +50mGal over the Australian Shelf decreasing to 0mGal over the Timor - Tanimbar - Aru Troughs, before decreasing further to -30 to -50 mGal over the thickened crust of the forearc. Anomaly values in the north of the forearc create a steep, northerly positive, gradient reaching 180 to 200mGal at the junction of the continental and arc crusts. Gravity profiles over the Kai block also have a form common to the Banda Arcs except for the eastern margin where instead of values decreasing away from the Australian Shelf they rise steeply to 150 to 200mGal. This elongated high is probably due to thin crust related to present-day crustal extension in Eastern Indonesia.

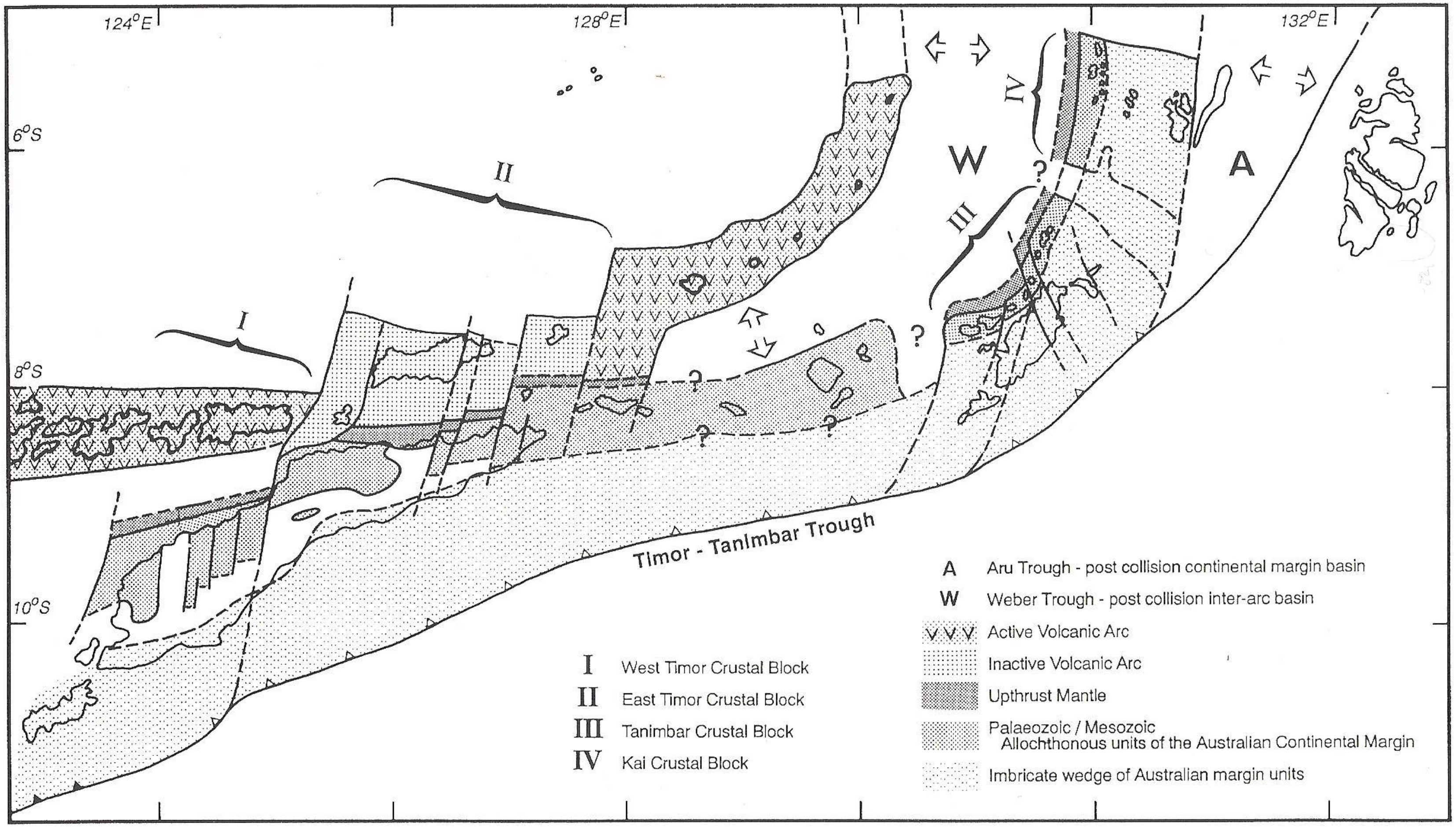
The curved form of the Banda Arcs probably results from the NNE-SSW pincer convergence of the Irian Jaya continental crustal block from the north, the NNE convergence of the Australian Continental margin from Timor to Tanimbar and the presence of the New Guinea Continental block to the east. The NNE-SSW convergence has led to ESE-WNW extension of the Banda Sea region, particularly in the Weber - Kai -Aru region, which has tectonically overprinted the earlier, arc/continental collision, compressional phase. Strike-slip faulting and associated rotation and translation of crustal blocks is at a maximum in this eastern region.



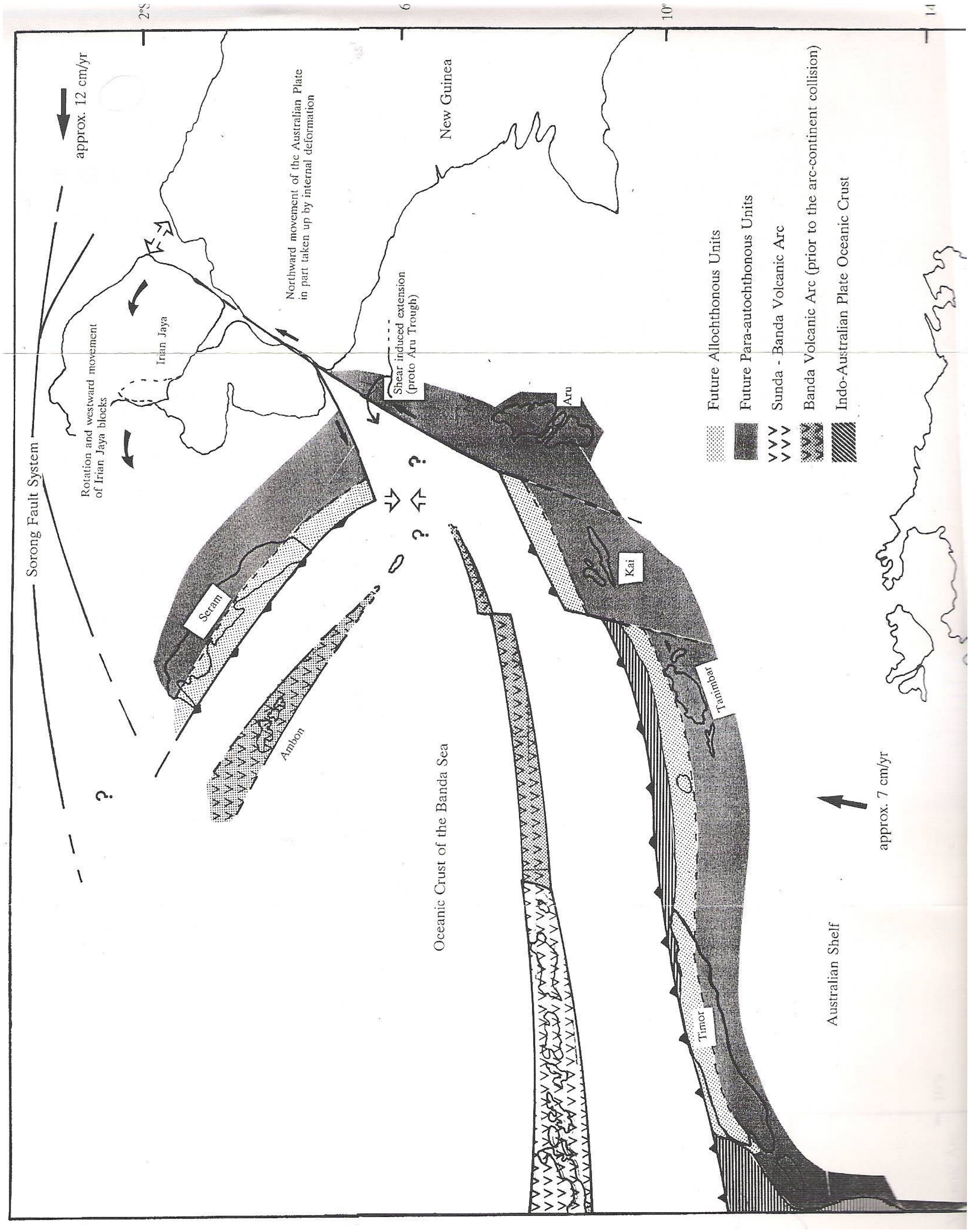
Introductory Figure 1. Eastern Indonesia Location Map adapted from Bowin et al. 1980



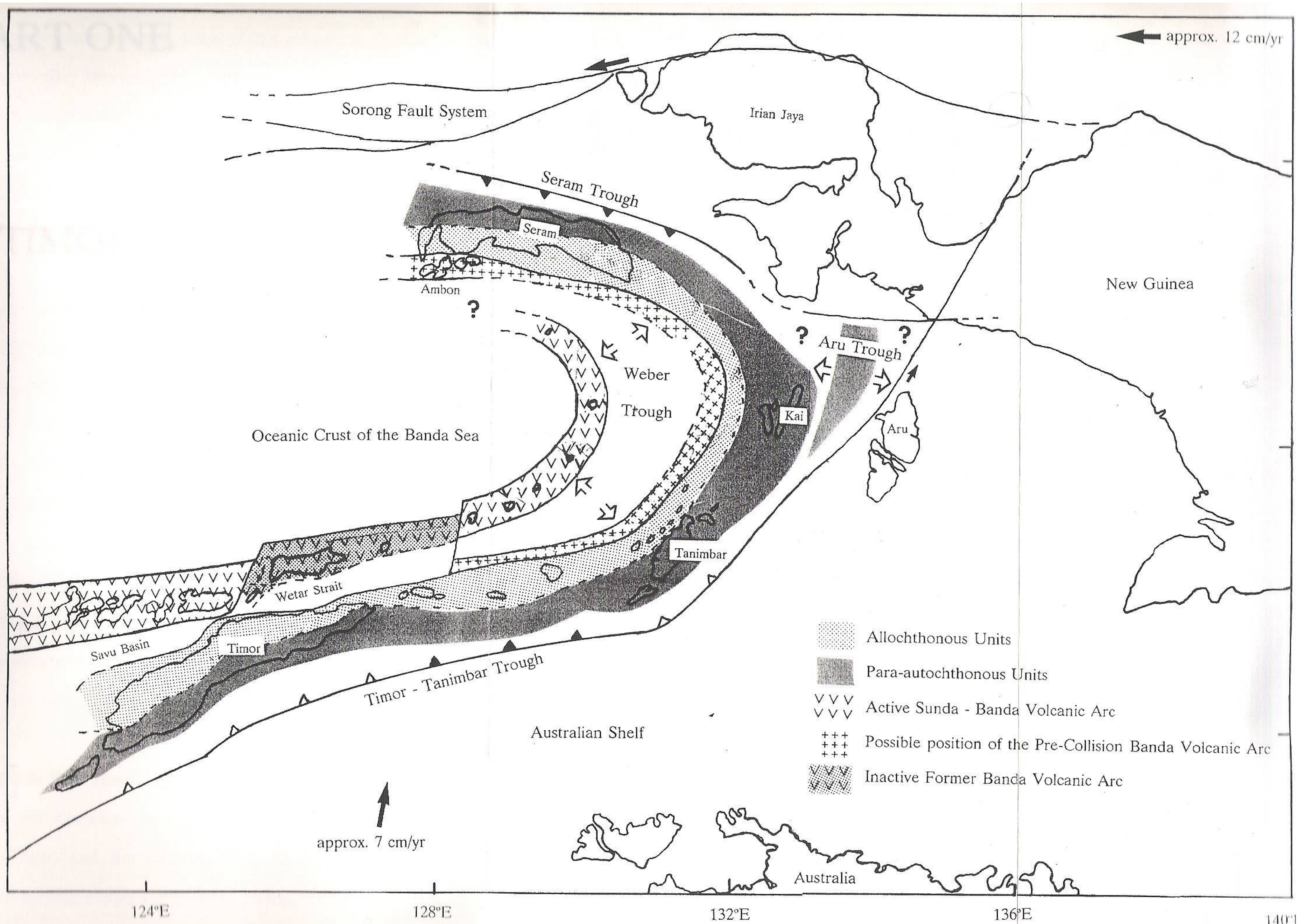
Introductory Figure 2 - General Bathymetric Map of Eastern Indonesia



Introductory Figure 3. Crustal Blocks and Tectonic Elements in Southern Eastern Indonesia based on geophysical data examined in this thesis.



Sorong Fault System
approx. 12 cm/yr
Rotation and westward movement of Irian Jaya blocks
Irian Jaya
Northward movement of the Australian Plate in part taken up by internal deformation
New Guinea
Shear induced extension (proto Aru Trough)
Aru
Seram
Kai
Ambon
Oceanic Crust of the Banda Sea
Tanimbar
Timor
Australian Shelf
approx. 7 cm/yr
Future Allochthonous Units
Future Para-autochthonous Units
Sunda - Banda Volcanic Arc
Banda Volcanic Arc (prior to the arc-continent collision)
Indo-Australian Plate Oceanic Crust



INTRODUCTORY FIGURE 5 Present-day Plate Tectonic Units of Eastern Indonesia.

CHAPTER 1.1

THE ON-SHORE GEOLOGY OF TIMOR

1.1.1 THE HISTORY OF GEOLOGICAL EXPLORATION

The geology of Timor has been studied since the early years of this century when it first became possible to travel to the interior. Hirschi(1907) made two traverses across the island noting that it was structurally complex and composed of Permian, Triassic, Jurassic and Tertiary strata. Some of the results of Weber's survey in 1910-11 were published by Umbgrove(1935). In the years 1947-48 a survey of East Timor was conducted on behalf of the Royal Dutch Shell Group by Escher and Grunau(1953,1956,1957a,1957b). In 1955 the then Portuguese Government of East Timor funded a geological survey of the region by Gageonnet and Lemoine, who published their findings in a number of papers (Gageonnet and Lemoine 1957a,1957b,1957c,1957d,1958; Gageonnet, Lemoine and Trumpy 1959; Lemoine 1959). The next phase of geological and geophysical exploration was carried out on behalf of Timor Oil Ltd between 1958 and 1964. The main publication resulting from this work was that of Audley-Charles(1968), which reflects his field experience in East Timor and includes information from a number of Timor Oil company reports. This publication is the main reference document for the geology of East Timor and is still the base from which all later geological syntheses stem. At the time of writing (July 1988) the stratigraphy and the geological map of East Timor are being revised by Lumban Tobing at University College London, to include additional field information gathered since the original map publication plus a reinterpretation of air photographs.

Localised fieldwork was carried out in East Timor by British and Australian groups until the departure of the Portuguese administration in 1975. The British group's work is summarised in Carter, Audley-Charles and Barber(1976). The Australian work was published in a number of papers, notable amongst which are Grady(1975), Grady and Berry(1977), Chamalaun(1977), Chamalaun and Grady(1978) and Berry and Grady(1981). Meanwhile, Norvick(1979) and Hamilton(1979) published reviews of the geology, structure and tectonic environment of the region.

In West Timor, geological mapping by the Geological Research and Development Centre, Bandung (GRDC) was completed in the late 1970's followed by publication of a 1:250,000 scale map (Rosidi, Suwitodirdjo and Tjokrosapoetro, 1979). At the same time, and continuing to this day, a number of workers from the University of London Consortium for Geological Research in SE Asia have conducted localised geological studies in West Timor.

During the 1970's and 1980's there were a number of marine cruises which examined various geophysical aspects of the Banda Arcs. Aspects of the data gathered by these cruises are discussed in Chapter 1.3, section 1.3.4 and Chapter 1.4, section 1.4.2.

The latest large scale study of the Banda region was the Dutch/Indonesian Snellius II Expedition in 1984-85. This was a joint marine and land study designed to enable the formulation of a detailed hypothesis of the creation of the Banda Arcs. At the time of writing results have not been published.

1.1.2 INTRODUCTION TO THE STRATIGRAPHY OF TIMOR

The history of geological mapping in Timor has been affected to a large extent by political constraints. Prior to the departure of the Portuguese government from East Timor the island was split in two, which resulted in separate teams operating either side of the political divide creating different names for equivalent geological units. As a result, the geological maps of East Timor (Audley-Charles,1968), and West Timor (Rosidi et al,1979), use different stratigraphic nomenclatures. This situation is presently being rectified by Lumban Tobing but his work is not completed. Consequently, the following description is largely based on the work of Audley-Charles(1968) and Rosidi et al (1979) but reference is made to the work of Lumban Tobing where appropriate. Others works are referred to when they contain information which influences the geophysical models.

The division of the stratigraphy into autochthonous, para-autochthonous and allochthonous units used by Audley-Charles(1968) will be adhered to, using the following loose definitions: the autochthon includes all units located where they were deposited; para-autochthonous units have clear Australian affinities, are strongly folded and faulted but have not been moved great distances since deposition; allochthonous units are those rocks that are thought to form flat-lying thrust sheets/nappes and their associated roots.

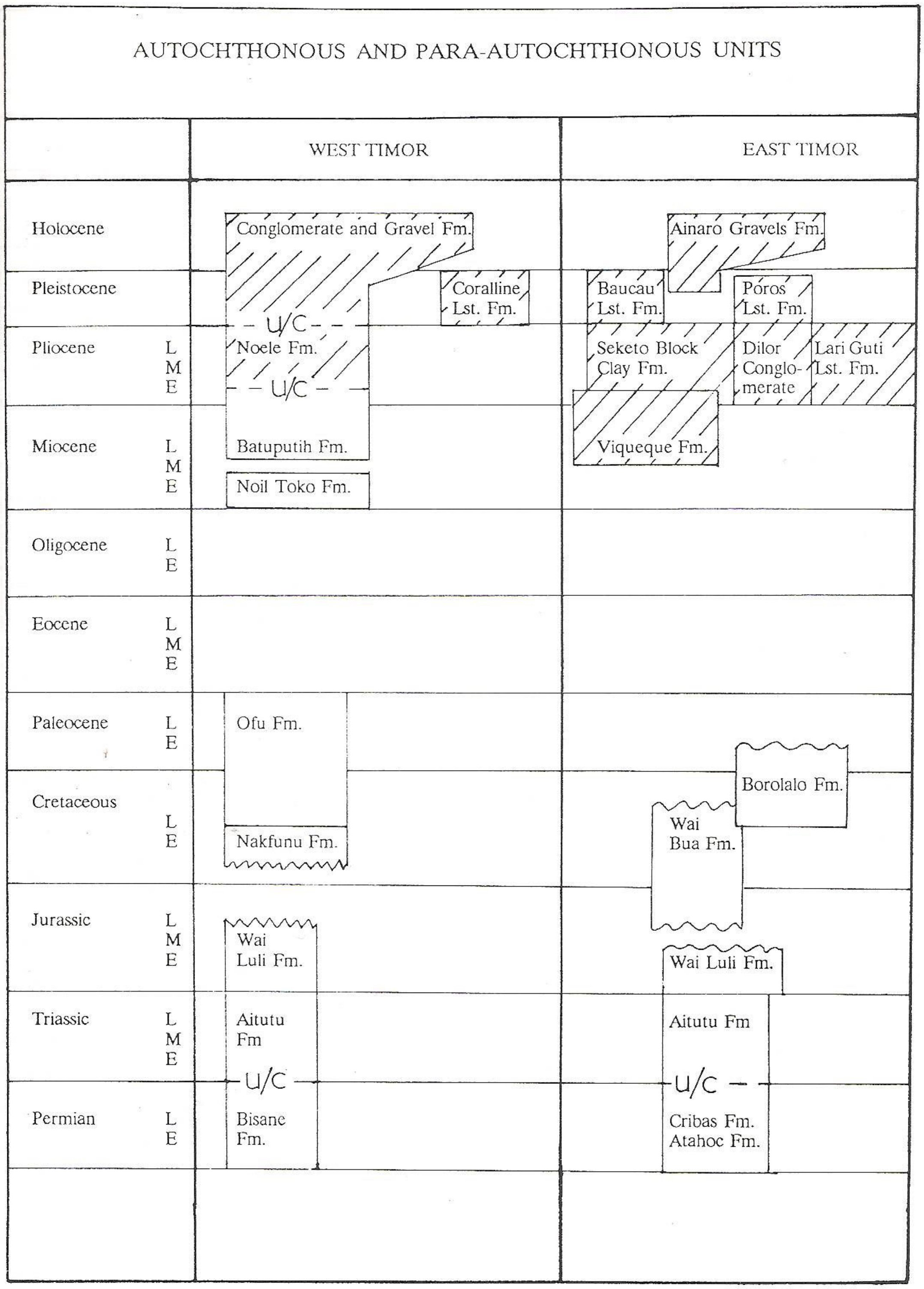


Table 1.1.1 Autochthonous and Para-autochthonous Units of Timor

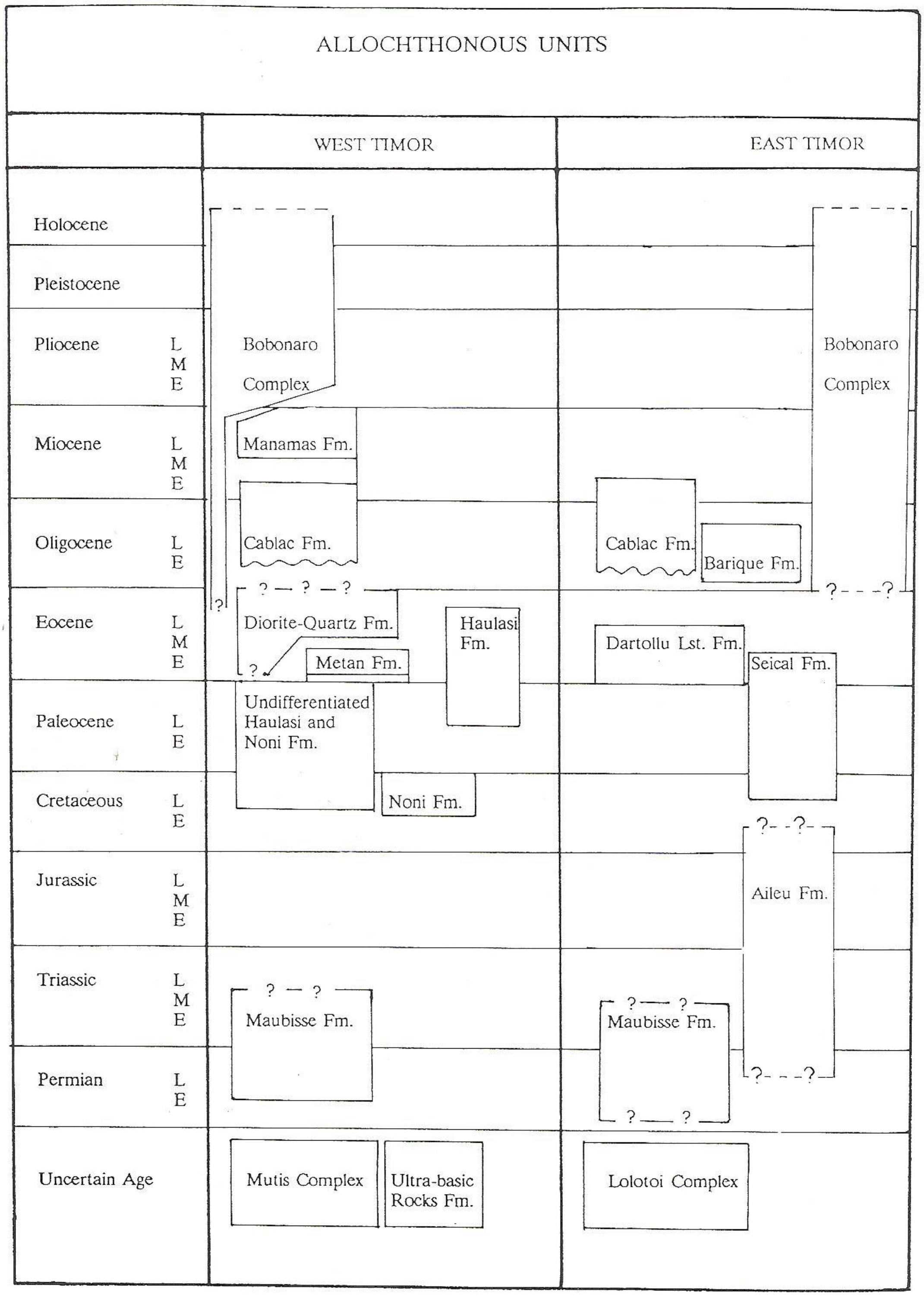


Table 1.1.2 Allochthonous Units of Timor

1.1.3 THE STRATIGRAPHY OF TIMOR

Nearly all of the descriptions in the following sections are taken from Rosidi et al(1979) for West Timor, and Audley-Charles(1968) for East Timor.

1.1.3.1 Autochthonous and Para-autochthonous Units

PERMIAN - In West Timor the oldest unit is the Permian Bisane Formation consisting of 1000m of shale, sandstone, calcareous sandstone and thin intercalations of chloritized lava. In East Timor the Permian is divided into the earlier Atahoc Formation, consisting of quartzites, shales, calcilutites and calcareous nodules deposited as deep water flysch, and the later Cribas Formation which consists micaceous shales, siltstones with quartz-arenites, calcilutites and nodules.

TRIASSIC - in West Timor the lower part of the Aitutu Formation consists of siltstone, marl and limestone with intercalations of sandstone, chert and crystalline limestone. In the upper part calcilutite and shale predominate. The depositional environment is thought to have been deep marine. In both East and West Timor the base of the Aitutu is unconformable on the Permian Bisane Formation. In East Timor the Aitutu consists of radiolarites, limestones, cherts and shales. The Babulu Member is stratigraphically the youngest part of the formation and consists of Middle Triassic shales, sandstones and siltstones. The Talibellis Member is Rhaetian in age, outcrops in central Timor and consists of shales and limestones. The Aitutu Formation in both East and West Timor is approximately 1000m thick.

JURASSIC - in West Timor the Wai Luli Formation ranges in age from the latest Triassic to Upper Jurassic and consists of approximately 450m of calcarenite, shale, marl and greywacke. The unit is thought to have been deposited in a shallow marine environment. The base is conformable on the Triassic Aitutu Formation but is overlain unconformably by all other units. In East Timor the Wai Luli spans the Late Triassic to Middle Jurassic and is 1000m thick. Here the formation consists mostly of shale with calcilutites, marls, silts, arenites and conglomerates, together with red shales and gypsum and also lies conformably on the Upper Triassic Aitutu Formation.

CRETACEOUS - in West Timor the deep-marine sediments of the Nakfunu Formation include cherty radiolarian siltstone, shale, radiolarian chert and marl. Well-bedded manganese and ferro-manganiferous rocks occur. Thickness is estimated to be 600m. The Nakfunu is the equivalent of the lower part of the Wai Bua Formation in East Timor which ranges in age from the Late Jurassic to the Late Cretaceous. In total the Wai Bua consists of 500m of radiolarites, radiolarian shales, cherts, calcilutites and manganese nodules.

LATE CRETACEOUS TO PALEOCENE - in West Timor the Ofu Formation comprises approximately 250m of deep marine calcilutite, shale and intercalated radiolarian chert. Stratigraphic relationships have not yet been determined but the equivalent in East Timor may be the Borolalo Limestone Formation which is thought to be a lateral variation of part of the Wai Bua Formation and consists of 200m of calcilutites, biocalcarenites and cherts of Maastrichtian to Campanian age.

EARLY MIOCENE - in West Timor the Noil Toko Formation (Rosidi et al,1979) includes conglomerate, conglomeratic limestone, globigerina limestone, calcareous sandstone, marl, tuff and shale. Conglomerate clasts are derived from the allochthonous Mutis Complex (see below) with schist, amphibolite, slate and chert, together with volcanic rocks of the allochthonous Maubisse Formation. No autochthonous or para-autochthonous rocks of this age have been recorded in East Timor.

LATE MIOCENE TO PLIOCENE - in West Timor the Batuputih Formation is the oldest formation in the Viqueque Group, and is in places conformably and others unconformably overlain by the Noele Formation of the same group (see below). The Batuputih is made up of calcilutite, tuff, marl and arenaceous limestone in the lower part, and marl, calcarenite, sandstone and conglomerate in the upper. Maximum thickness is about 1100m. In East Timor the Viqueque Formation (which is only part of the Viqueque Group) consists of 800m of sandstones, siltstones, mudstones and shales deposited on top of a basal conglomerate. It is a molasse deposit resulting from the main orogenic event on Timor. The Lari Guti Limestone Formation consists of 75m of fringing coral reefs with calcarenites. The Dilor Conglomerate Formation is a deltaic sequence of cross-bedded conglomerates, sands, silts and marls. The Seketo Block Clay Formation is 20m of pebbly mudstone with interbedded marls deposited in a submarine slope environment. All of the above, except for the Batuputih Formation, were formerly considered to be para-autochthonous but have now been placed in the autochthonous Viqueque Group (Lumban Tobing,pers.comm.,1988).

PLIO-PLEISTOCENE - the Noele Formation is part of the Viqueque Group in West Timor and consists of approximately 700m of sandy marl intercalated with sandstone, conglomerate and a few dacite tuff layers. There are rapid lateral facies changes. The marl is rich in globigerinids and other pelagic forams. The formation is overlain unconformably by the Coralline Limestone and Conglomerate and the Gravel Formations (see below).

PLIOCENE TO HOLOCENE - the Conglomerate and Gravel Formation in West Timor forms river terraces which reach elevations of 45m above the present flood-plains. Conglomerates, gravel, cobbles and boulders are the main constituents, cemented in the lower parts by calcite or limonite, but loose in the upper. The unit is the equivalent of the Ainaro Gravels Formation in East Timor which is now restricted in age to the Pleistocene and placed within the Viqueque Group.

PLEISTOCENE - the Coralline Limestone Formation in West Timor consists of fringing coral-algal reefs that are now uplifted and reach 1300m elevation in places. The unit is commonly white to yellowish and exhibits rough and cavernous surfaces. The upper part is massive while the lower shows signs of bedding tilted 3-5 degrees. Maximum thickness is 300m. The equivalent in East Timor is the Baucau Limestone Formation which has a similar lithology. Also in East Timor, the Poros Limestone Formation consists of 20m of bedded, algal limestone considered to be of lacustrine origin. This unit is thought to be Pleistocene in age but may be younger. The East Timor Suai Formation is poorly exposed and most information has been gathered from drill cores from south East Timor. It is an unconsolidated molasse deposit consisting of gravels and fine silts, often rich in forams. Maximum thickness on-shore is approximately 1000m but may be greater off-shore on the margins of the Timor Trough.

1.1.3.2 The Allochthonous Units of Timor

UNCERTAIN (?) - the Mutis Complex in West Timor and the Lolotoi Complex in East Timor are considered by all workers to be equivalents. The Mutis is described by Rosidi et al(1979) as consisting of low to high grade metamorphic rocks including slate, phyllite, schist, amphibolite, quartzite, gneiss and granulite. Only small amounts of slate occur. Phyllite types are sericite, albite-arkose, graphite and quartzose. Schist types are epidote-chlorite-actinolite, quartz-carbonate-muscovite-chlorite, garnet-piedmontite-quartzose. Amphibolite is the major rock type and includes plagioclase, epidote, and garnet-gneiss varieties. Granulites are amphibolite-garnet-gneiss, staurolite-kyanite-garnet-gniess and pyrope-hornblende-anorthosite. In West Timor the complex is intruded by metamorphosed dykes of diabasic and dioritic rocks and is tectonically overlain by the Permian Maubisse Formation (see below). Brown and Earle(1983) consider the Mutis/Lolotoi to be Mesozoic, based on an Early Cretaceous Rb-Sr whole-rock isochron age of 118 -/+38Ma obtained from pelitic rocks of the Boi Massif in West Timor. They subdivide the Mutis into two lithostratigraphic components: basement schists and gneisses; and the remnants of an ophiolite. The ophiolite remnant can be further subdivided into three: greenschists and metagabbro; layered amphibolite gneiss; metaperidotite with foliated tremolite and serpentinite. These sub-units are stacked in reverse lithostratigraphic order with the metaperidotites at the top and greenschists at the base. The ophiolite remnant has undergone one primary metamorphic event and is underlain by the polymetamorphic basement schists and gneisses. This lower unit consists of interlayered amphibolites and pelitic gneisses and schists which show a longer deformation history than the overlying ophiolite remnant. Brown and Earle(1983) consider that the decompression shown by the P-T paths in the lower unit was due to rifting and synmetamorphic ophiolite emplacement resulting from processes during the development of a convergent margin located in SE Asia during the Late Jurassic to Cretaceous.

The latest work on the Mutis and Lolotoi Complexes has been conducted by members of the 1985-1987 Snellius II Expedition. Sopaheluwakan et al(1987) broadly agree with Brown and Earle(1983) in stating that there is an inversion in the spatial distribution of the metamorphic zonation with respect to the structural sequences.

PERMIAN TO MIDDLE JURASSIC (?) - in West Timor the Maubisse Formation is restricted in age from the Permian to Middle Triassic and subdivided into two diachronous units, the oldest comprised of pillow lavas and the younger of limestones. The pillow lava is mainly basaltic and spilitic and includes trachyte, porphyry syenite and leucoandesite. Serpentine is commonly associated with the pillows. The limestone unit is commonly massive but shale, calcilutite and chert do interdigitate. The formation is rich in fauna, including ammonites, brachiopods, crinoids, corals and fusilinids, indicating a shallow water environment. In East Timor the Maubisse Formation has a similar lithology. Paleomagnetic analysis by Wensink et al(1987) suggests an Australian origin for the Maubisse Formation, a view supported by recent palaeontological province analysis (S.Barkham,pers.comm.,1988).

EARLY PERMIAN TO LATE EARLY CRETACEOUS - in East Timor the Aileu Formation of Audley-Charles(1968) is essentially a flysch which becomes more siliceous northwards until near the north coast of East Timor where metaquartzites, micaschists, marbles, metabasics and amphibolites outcrop (Berry and Grady,1980). There is a clear metamorphic zonation from low greenschists in the southwest to upper amphibolite on the north coast. The metamorphic maximum may have occurred in the Jurassic, affecting Paleozoic sediments deposited in a graben. The arc-continent collision in the Late Miocene/Pliocene ended the metamorphic phase by uplifting the Aileu Formation (Berry and Grady,1981). There is considerable debate concerning the tectonostratigraphic affinity of this formation, with some workers considering it to be possibly para-autochthonous. There is no equivalent in West Timor.

LATE JURASSIC TO EARLY PALAEOCENE - the Palelo Group of West Timor spans the Late Jurassic to Palaeocene time period but has not been differentiated into individual formations. The lower Palelo consists of spilite volcanic breccias with clasts of metamorphosed and deformed basalts. Earle(1979) closely relates the youngest units of the Lolotoi/Mutis Complex with the Palelo Group and uses the two to form the Lolotoi Unit. In the Late Jurassic the Palelo consists of cherty limestones and cherts, overlain in the Late Cretaceous by proximal turbidites. In the Palaeocene tuffs, agglomerates, lavas and siltstones were deposited.

CRETACEOUS (late?) - in West Timor the Noni Formation, of the Palelo Group, consists of deep marine, well-bedded radiolarian cherts, cherty limestones and clayey chert. The unit is highly deformed and the thickness is not known.

LATE CRETACEOUS TO MIDDLE EOCENE - in West Timor rocks of this age have clear similarities with the Noni Formation of Late? Cretaceous age and the younger Middle Paleocene-Middle Eocene Haulasi Formation (below) and is consequently called the

Undifferentiated Haulasi and Noni Formation of the Palelo Group. This combined unit is complexly tectonised and estimated to be 400m thick. In East Timor the Early Eocene Dartollu Limestone Formation was deposited and consists of marl, limestone and shale of a lagoonal facies type. Elsewhere in East Timor the late Cretaceous to Early Eocene is represented by two units. The earliest of the two is the Seical Formation which is lithologicaly similar to the Wai Bua Formation with radiolarites, radiolarian cherts, shales and marls. The older is the Borolalo Limestone Formation consisting of calcilutites and biocalcarenites.

MIDDLE PALEOCENE TO MIDDLE EOCENE - in West Timor the Haulasi Formation, Palelo Group is a shallow water deposit of conglomeratic greywacke, sandstone, shale and marl. Much material is derived from volcanic sources. Estimated thickness is 300m.

EARLY EOCENE - the Metan Formation, Palelo Group of West Timor is a 600m-thick agglomerate with a tuff matrix. Clasts are pumice, andesite and vitric tuff in a coarse tuff matrix. Lavas are andesitic but pyroxene basalts also occur. The upper part of the unit contains lenses of limestone and sandy marl with forams.

EOCENE(?) - in West Timor localised outcrops of Diorite-Quartz (formation name) diorite intrude Late Cretaceous to Early Eocene rocks. The diorite is fine to coarse grained and in places has a diabasic texture. Hornblende is common while pyroxene occurs in small amounts. No similar units are described from East Timor.

OLIGOCENE - in East Timor the Barique Formation is approximately 300m of dacitic and basic tuffs, pumice, basic pillow lavas and conglomerates. It was originally classified as autochthonous but at present its tectonostratigraphic position is undefined. However, the present author considers it to be allochthonous based on the observation of Audley-Charles(1968) that the Barique has an unconformable top and bottom, and has close field relationships with the undoubtedly allochthonous Lolotoi, Maubisse and Cablac Formations.

LATE OLIGOCENE TO EARLY MIOCENE - The Cablac Formation of East and West Timor, is estimated to be 800m thick and interdigitates in West Timor with the Noil Toko Formation. The Cablac overlies the Aitutu and Metan Formations and the Mutis Complex, with the base of the Cablac being marked by a conglomerate with clasts derived from the underlying units. The lower part of the Cablac includes calcilutite and oolitic limestone with calcarenite and calcirudite. Chert is often found in the limestone. Audley-Charles(1968) dates the 50m-thick Aliambata Limestone in East Timor as a Lower Miocene lateral variation of the Cablac, consisting of calcirudites rich in pelagic forams.

LATE MIOCENE - the Manamas Formation of West Timor comprises massive volcanic breccia with lava flows and tuff intercalations. The breccia includes olivine-bearing pyroxene basalt, augite andesite, nepheline syenite and trachyte. The matrix is tuffaceous and greenish, probably due to chloritisation. Lava flows are andesitic to basaltic, commonly forming pillows. The formation is mildly deformed with a 20-30 degree northward dip. The formation is dated at 5.9 -6.2 Ma (Abbot and Chamalaun,1976) with an approximate thickness of 1500m. The basal unit of the Manamas Formation has been thrust over a suite of Ultrabasic Rocks (formation name) of unknown age, consisting of basalt, lherzolite and serpentinite. The basalts are porphyritic and vesicular, while the lherzolite is fractured and in places serpentinised. Dark green, foliated, serpentinite is most common and contains magnetite and antigonite.

EOCENE? TO RECENT - the Bobonaro Complex of East and West Timor is made up of scaly clay and exotic blocks of various sizes. The scaly clay matrix is soft, multi-coloured, commonly slicken-slided and exhibits flow lines. Exotic blocks have been identified as being derived from the Bisane, Cablac, Maubisse and Ofu Formations together with the Mutis Complex. The age of the Bobonaro Complex is in doubt but forams range from Mesozoic to

Pliocene. Pre-Miocene forams are thought to be reworked. The thickness of the unit varies considerably across the island and no firm estimates have been made. Audley-Charles(1968) suggests that the Bobonaro is an allochthonous olistostrome deposited during the Eocene into a deep water zone north of the Australian margin. In contrast Barber et al(1986) maintain that the Bobonaro is the result of over-pressured and under-consolidated clays within an imbricate wedge, moving to the surface as diapirs along wrench faults. As the diapirs move up they erode rock from surrounding country units. After eruption at the surface the shale and clasts can be carried considerable distances by gravitational and erosional processes.

1.1.4 TECTONOSTRATIGRAPHY

1.1.4.1 Introduction

As mentioned in the preceding sections of this chapter, the stratigraphy of Timor is complicated and is being actively studied by many groups. As would be expected of a complex fold and thrust mountain belt there is some debate over the classification of stratigraphic elements in the three categories defined as autochthonous, para-autochthonous and allochthonous. By definition, the autochthon has not moved relative to it's basement, the para-autochthon is still in contact with it's basement but has moved relative to it and the allochthon is no longer in contact with it's basement.

1.1.4.2 Tectonostratigraphic Models

There are three main tectonstratigraphic models for Timor. The overthrust model describes Timor in terms of southward-travelled, overthrust nappes of the Banda allochthon that now overlie the para-autochthon. Block-faulting has in many places obscured the earlier thrusting. This model is supported by Audley-Charles(1968,1981,1986), Carter et al(1976), Barber et al(1977), Norvick(1979) and Rosidi et al(1979).

The imbricate or accretionary model, is championed by Jacobson et al(1978) and Hamilton(1979), and classifies Timor as a chaotic melange scraped from the descending Australian Plate, resulting in an imbricate wedge.

The upthrust model is described by Grady(1975), Crostella(1977), Grady and Berry(1977) and Chamalaun and Grady(1978) in which uplift due to isostatic rebound has occurred following the rupture of the subducted oceanic portion of the Australian Plate from the continental portion. This rebound is responsible for the prevalence of high-angle normal faults throughout Timor and the absence of major, widespread thrust faulting. Local imbrication is recognised but this model claims nappes are absent.

The vein developed in this thesis is that all three models are supported in part by the available geological and geophysical data but no one model appears to be entirely applicable to all of Timor. Thrusting and nappe emplacement has certainly occurred; there is ample evidence for high angle normal faulting; and imbricate wedges are evident in southern Timor. Additionally, study of the topography, coastal form, alignment of geological units, Landsat images and the gravity data suggest that there has been extensive sinistral NNE-SSW wrench faulting throughout Timor.

	AUTOCHTHONOUS AND PARA-AUTOCHTHONOUS	ALLOCHTHONOUS
HOLOCENE	Recent deposits	Bobonaro
	Ainaro Gravels	Scaly
PLEISTOCENE	Coralline Lst. Noele F.	Clay
	Batuputih F.	
PLIOCENE		
MIOCENE		Manamas F. Ultra Basic F.
	Noil Toko F.	Cablac Lst.
OLIGOCENE		
EOCENE		Undiff. Haulasi Same Lst.
		Haulasi Form. Metan Form.
PALEOCENE	Ofu Formation and Seical F.	
		Noni F.
CRETACEOUS	Wai Nakfunu	NoniFormation Palelo
	Bua Formation	Group
JURASSIC	Wai Luli Formation	
		Aileu Formation
TRIASSIC	Aitutu Formation	
PERMIAN	Cribas F. | Bisane F.	
	Atahoc F. |	Maubisse Formation
UNCERTAIN AGE		Lolotoi/Mutis Complex

TABLE 1.1.4.1

CHAPTER 1.2

TIMOR REGION GRAVITY DATA

1.2.1 INTRODUCTION

A new Bouguer anomaly map of the island is presented (rear pocket). The data have been compiled from eight surveys spanning four decades. Five of these surveys, by Shell in 1948 (De Snoo, 1948), Timor Oil in the late 1950s (Audley-Charles,1959), Flinders University, Australia (Chamalaun et al,1974), Imperial College, London (Milsom and Richardson,1976) and the Portuguese Missao Geografica de Timor (Botelho,1978), were in East Timor. The Portuguese survey also covered the former enclave of Ocussi, West Timor and the island of Atauro to the north of Timor. West Timor was surveyed by the Geological Reseach and Development Centre, Bandung between 1977-79 (Simamora and Untung,1983). Data from two marine cruises by the R/V Thomas Washington in 1981 and the R.R.S.Charles Darwin in 1988, have been used in contouring the gravity field in the Wetar Strait between Timor and Wetar (Fig.1.2.1.1).

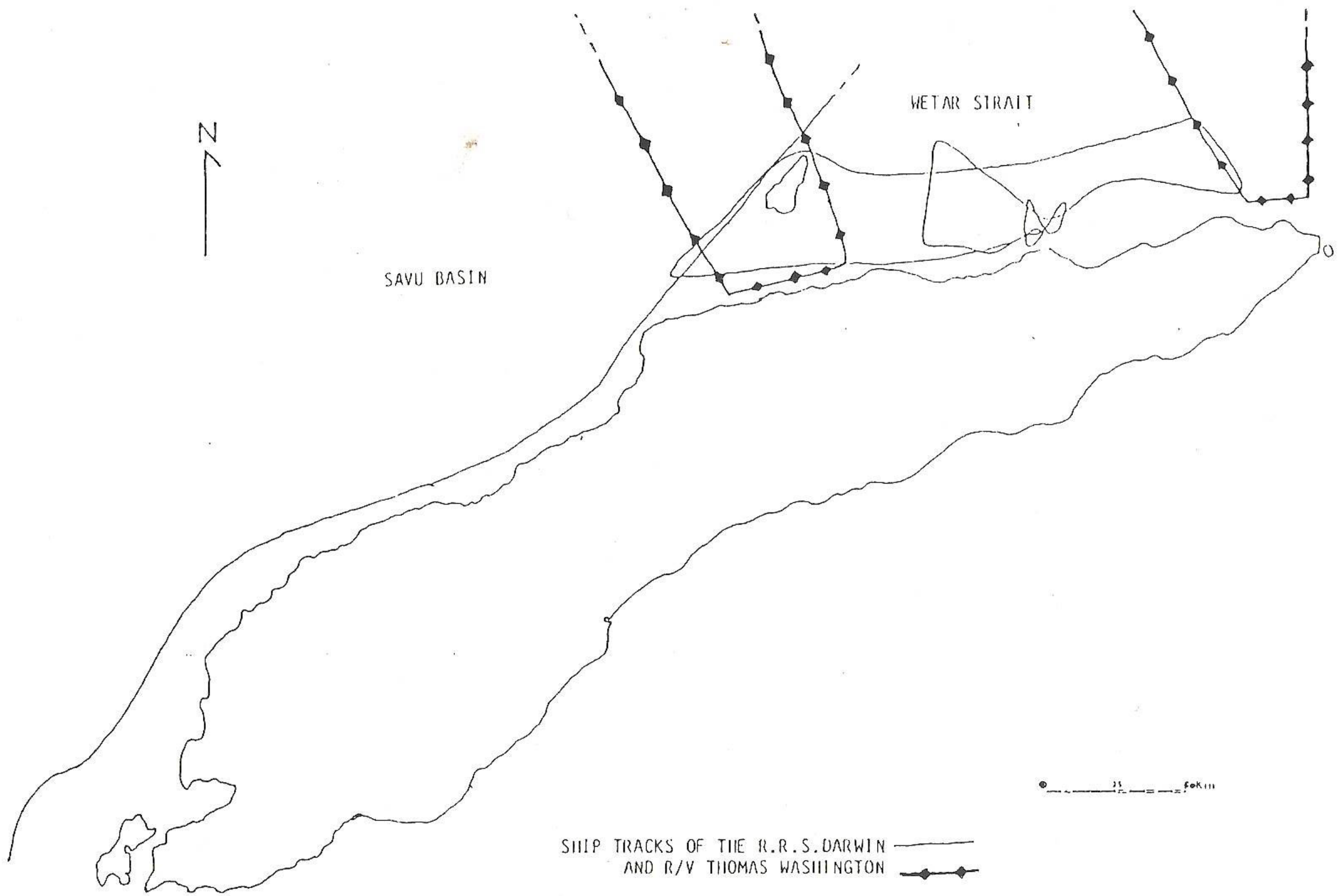


FIGURE 1.2.1.1 Ship track chart

1.2.2. EAST TIMOR GRAVITY SURVEYS USED IN THIS STUDY

Data from five surveys between 1948 and 1976 have been gathered together. The oldest survey was that conducted by DeSnoo in 1948 for Companhia Ultramarin de Petroleos, part of the Shell Group (henceforth known as the Shell survey). This survey was undertaken for oil exploration and as a result gravity stations are concentrated in the southern half of East Timor. However, a traverse was also made from Baucau in the north to Carabau in the south, defining the regional gravity gradient (DeSnoo,1948. This report Fig.1.2.2.1).

Between 1959 and 1962 Timor Oil carried out an extensive gravity survey across the southern half of East Timor. Again economic considerations were paramount, consequently north-south traverses were not made. The survey was largely designed to extend the former Shell survey further to the west (Fig.1.2.2.2).

In August 1973 a gravity survey of East Timor was carried out by F.H.Chamalaun of Flinders University of South Australia (Chamalaun,1976). A further survey completed in 1974 by A.R.Richardson of Imperial College is also incorporated in this study (Milsom and Richardson,1976). Both surveys were designed to study the gravity gradient across East Timor, the Bouguer anomalies changing from some +130 mGals in the north to -50mGals in the south. Consequently the surveys traversed the north-south Dili to Same road with additional stations scattered along the northern coastal road (Fig.1.2.2.3).

The results of the fifth survey were published by the Portuguese Missao Geografica de Timor in 1978 (Botelho,1978). The work was carried out over a number of years as part of a programme of regional research by the then Portuguese administration of East Timor. This survey has an even distribution of gravity stations throughout East Timor (Fig.1.2.2.3). Figure 1.2.2.4 is a compilation of all of the gravity stations.

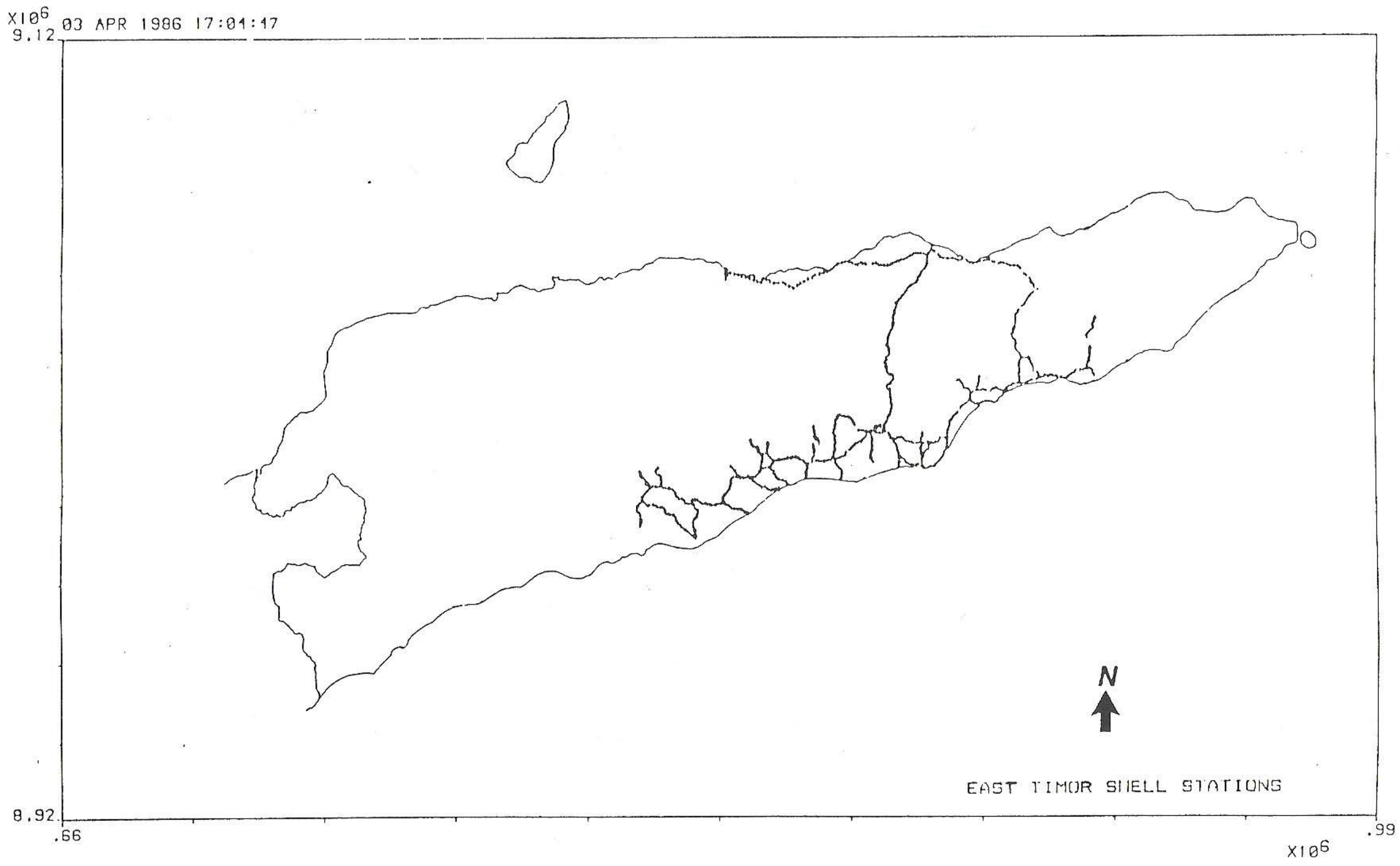


FIGURE 1.2.2.1 East Timor Shell stations

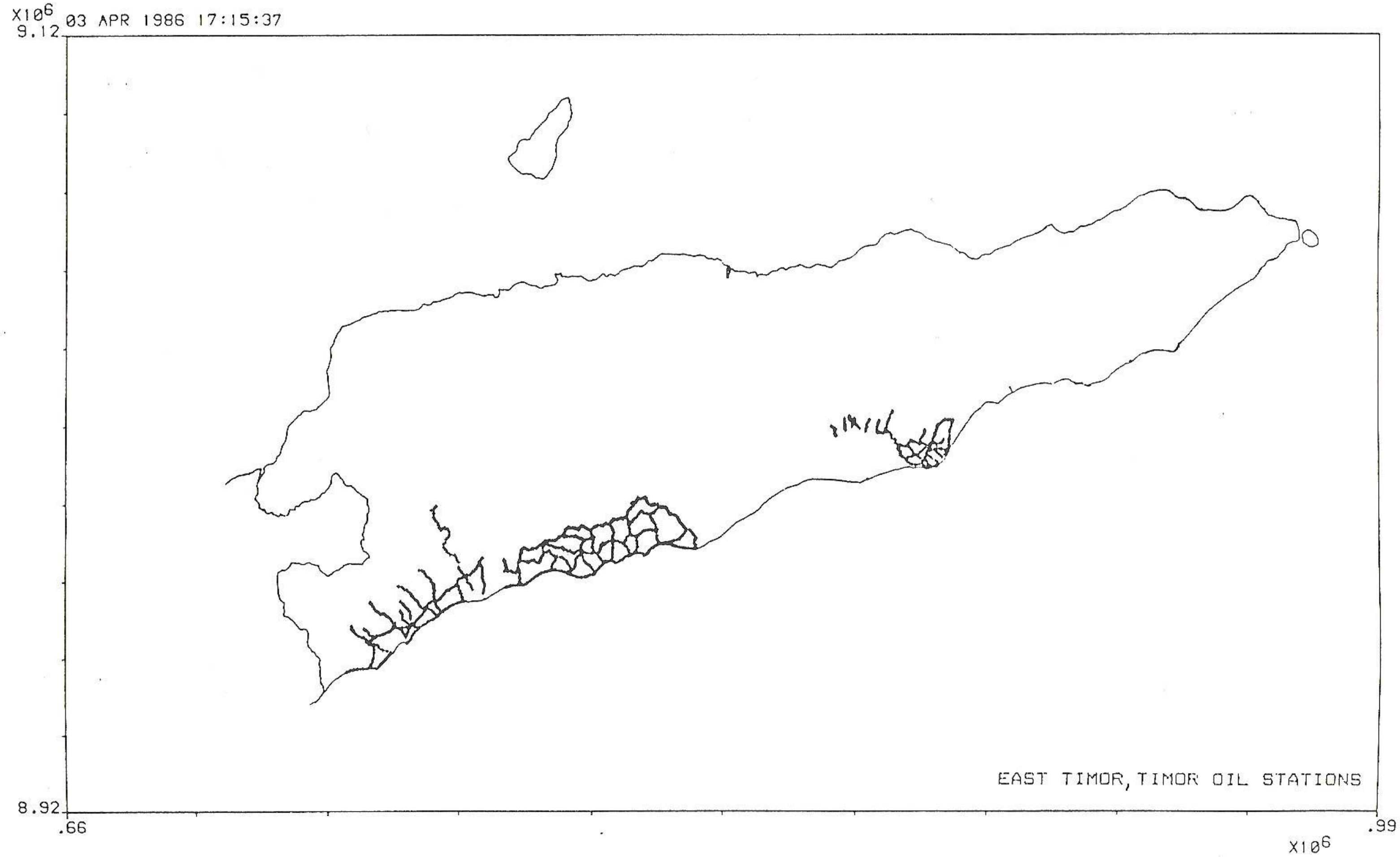


FIGURE 1.2.2.2 East Timor Timor Oil stations

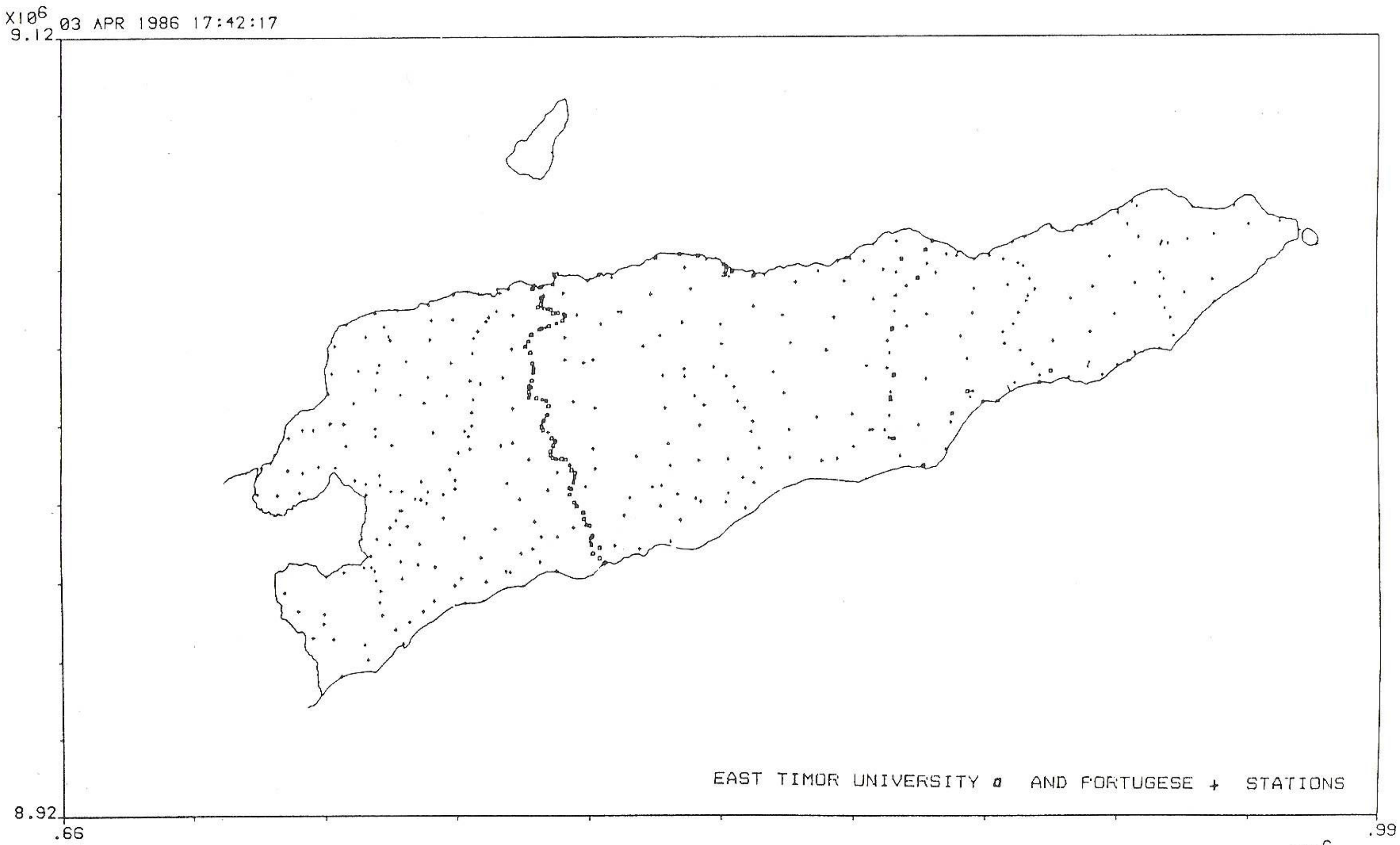


FIGURE 1.2.2.3 East Timor University and Portuguese stations

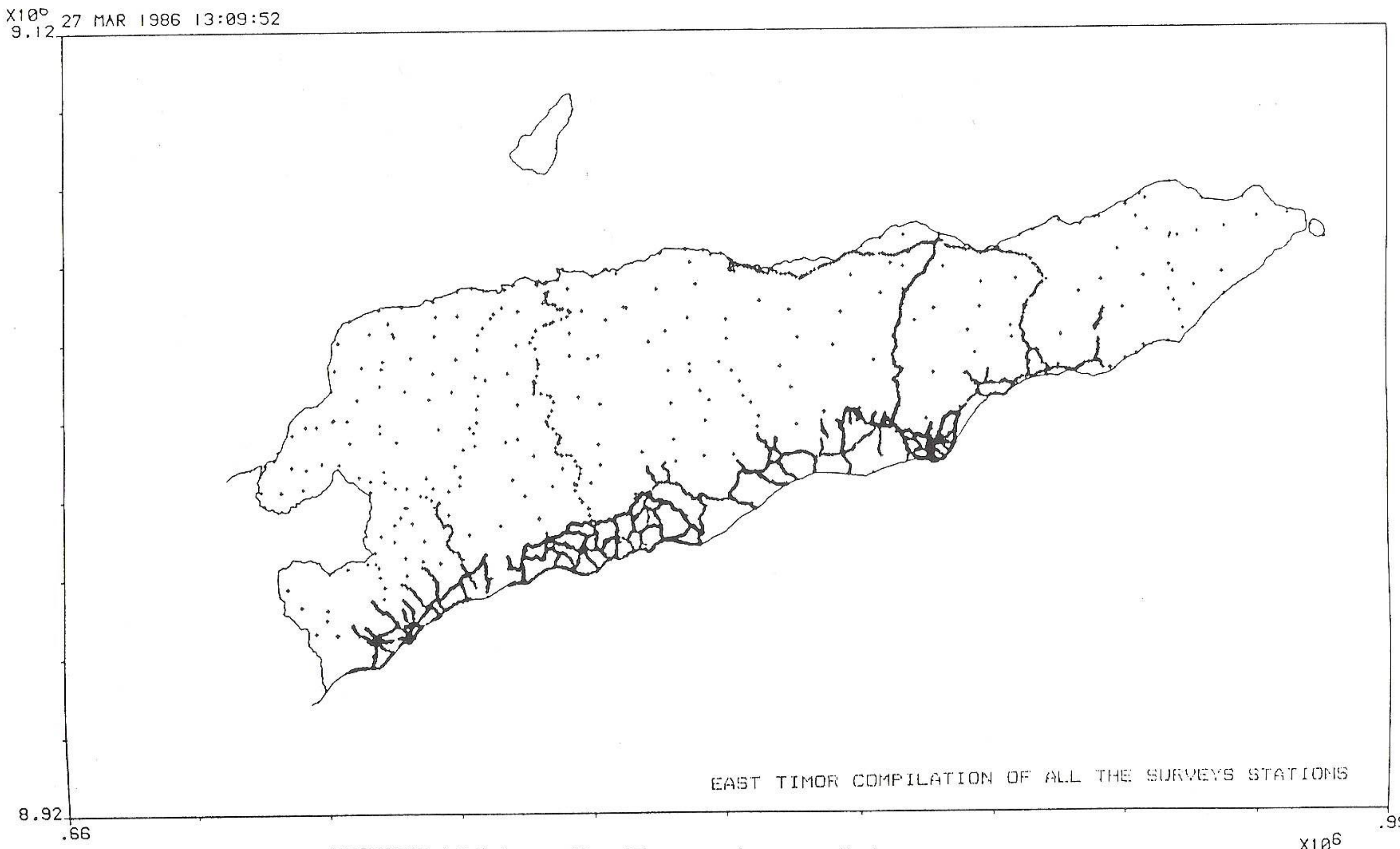


FIGURE 1.2.2.4 East Timor station compilation map

To produce a Bouguer anomaly six principal facts must be provided for each gravity station, these being 1) a station number, 2) a latitude 3) a longitude, 4) an elevation, 5) an observed gravity value and 6) a density. As can be seen from Table 4.2.1, the two oldest surveys in East Timor are lacking in some of these principal facts.

	Shell	**Timor Oil**	**Flinders Univ.**	**Imperial Coll.**	**Missao Geografico**
Elev.	yes	for most	yes	yes	yes
Lat.& Long.	no	no	yes	yes	yes
Obs. Grav.	no	for most	yes	yes	yes
Boug. Anom.	yes	yes	yes	yes	yes

Table 4.2.1

Prior to the publication in 1967 of the Portuguese Missao Geografica de Timor(MGT) 1:50000 scale topographic maps no reliable large scale maps were available for East Timor. The surveying of East Timor was begun by the MGT in 1954 and eventually resulted in 37 sheets at 1:50000. Contour intervals are 25m, and there are numerous spot heights. Projection is Universal Transverse Mercator (UTM) using the International Ellipsoid and a central meridian of 123°E of Greenwich. The UTM coordinate system has been adopted in this study as it is a metric rectangular system well suited to the production of maps via a digitiser and plotter.

1.2.2.1 SHELL DATA

The Shell survey data was made available by Shell International Petroleum and took the form of a listing of station numbers, elevations, locations in a local system and Bouguer anomalies. Problems to be overcome were:

1) The survey was conducted before the availability of reliable large scale topographic maps and consequently station locations were derived from the survey's own kilometre grid system. Therefore, the stations had to be relocated in latitude and longitude on the Portuguese 1967 topographic maps.

2) Latitude corrections were made using gradients calculated from the 1930 International Gravity Formula and gravity values were not tied to an international network. The values had to be recomputed using the 1967 International Gravity Formula and tied to the IGSN71 International Gravity Network.

3) Only Bouguer anomaly values were available but observed gravity values had to be back-calculated if new Bouguer anomaly values, adjusted to the present day gravity system, were to be computed.

The station coordinates were recorded in a local system as distances north and east of Beaco village on the south coast, distances south and west being negative. Unfortunately the exact point of origin of the grid has been lost and so a direct mathematical transformation to absolute position in latitude and longitude is not possible. Initially all the data was placed in computer files and stations were plotted out by a Benson plotter to a scale of 1:50000. The 1:50000 scale was chosen to match the Portuguese topographic maps which had already been copied onto stable base draft-film. The aim was to relocate the Shell stations using the topographic maps and to record the relocation on the draft-film copies. The relocation of the stations involved a comparison of the Benson plotted locations with features on the topographic maps. Fortunately the majority of stations surveyed were along roads, rivers or the coastline, enabling the relocation of strings of stations at their beginnings or ends, or where they crossed road and river junctions. Along coasts, the recorded station elevations, and the close match of the station positions with the coastline, suggested that the survey teams followed coastal paths. These paths are nearly always within one or two meters, of the high water mark. This enabled the coastal stations to be accurately relocated on the draft-film copies of the topographic maps.

It was found that the majority of stations required little adjustment to their absolute positions, the overall shift being of the order of 50m. Additional control was obtained by comparing the known height for each station with the 25m contours and spot heights on the Portuguese maps.

The relocation of stations not on roads or rivers presented more of a problem. However, East Timor has numerous tracks between villages and outlying agricultural areas which were often used by the survey team. It is reasonable on an island as rugged as East Timor to suppose that these tracks would not have shifted any appreciable distance between 1948, the time of the survey, and 1967, the publication date for the topographic maps; stations along tracks are presumed to be relocated only marginally less accurately than those on roads.

However, where the survey crossed open country there are frequently no tracks marked on the topographic maps. This problem has been overcome by a mixture of knowledge of the local conditions, gathered knowledge of survey practice in East Timor and a comparison of known station heights with the elevations shown on the Portuguese topographic maps.

Survey teams in East Timor have an attitude that is common to all surveys operating in rugged terrain - they are reluctant to gain or lose elevation. Commonly when surveying across country this entails following ridges or moving along valley floors. However, valley floors were not favoured by the Shell team presumably because the vegetation was too dense. More often than not the Shell team traversed along valley sides attempting to maintain a constant elevation.

Survey lines often kink around a village even if the track the survey was following runs through the settlement. Timor villages are surrounded by thorn hedges and gates designed to keep the village pigs in; to move through these pickets is difficult and so survey teams preferred to by-pass the village.

Timor has a tropical savannah climate with two markedly different seasons; one wet, the other dry. The climate controls gravity surveying in a number of ways. Firstly, all field work has to be carried out in the dry season because the roads and rivers are frequently impassable in the wet season. Secondly, not only are the roads passable in the dry season but so are the rivers, not for sailing up but for walking along. Timor is relatively arid compared to most other islands of Indonesia and the rivers commonly drain away during the dry season becoming route-ways into the interior. As a result, relocated Shell stations are often in the middle of rivers. Thirdly, Timor is a rugged island so that during the wet season flash floods carry away river banks and sections of road. As a result roads followed by the survey team in 1948 deviate, often quite sharply, from the position of roads marked on the 1967 topographic maps. This is only noticeable at river crossings, where the road follows a river bank, or in regions with steep slopes, and is nearly always localised within 50 to 100m of a river crossing or steep ravine. These deviations did not pose a great problem when relocating stations, it being assumed that the original survey line traced the former road or river position.

Once a single string of stations had been relocated on a 1:50000 scale map, the rest of the stations on the map frequently required little alteration in position. This indicates that there were few relative discrepancies in the original Shell station locations and that the Shell local system closely matches the grid of the Missao Geografica de Timor.

It should be noted that the foregoing comments on survey practice and local knowledge also apply to the Timor Oil stations, which had to be relocated in a similar manner.

After the stations had been plotted on the stable base draft-film copies of the topographic maps, their positions were digitised, output being in Universal Transverse Mercator (UTM) coordinates. The digitising process is described in detail in section 1.2.2.6.

The data made available to this study included Bouguer anomaly values computed using the 1930 International Gravity Formula. It was necessary to bring these values in line with the Portuguese and university surveys which were based on the 1967 International Gravity Formula and were tied to the IGSN71 International Gravity Network.

1930 International Gravity Formula:

$$g=978049 \ (1+0.0052884 \ \mathrm{Sin}^2 L - 0.0000059 \ \mathrm{Sin}^2 2L) \ \text{milligals}$$

where L is the latitude.

1967 International Gravity Formula:

$$g=978031.85 \ (1+0.005278895 \ \mathrm{Sin}^2 L + 0.000023452 \ \mathrm{Sin}^4 L) \ \text{milligals}$$

where L is the Latitude.

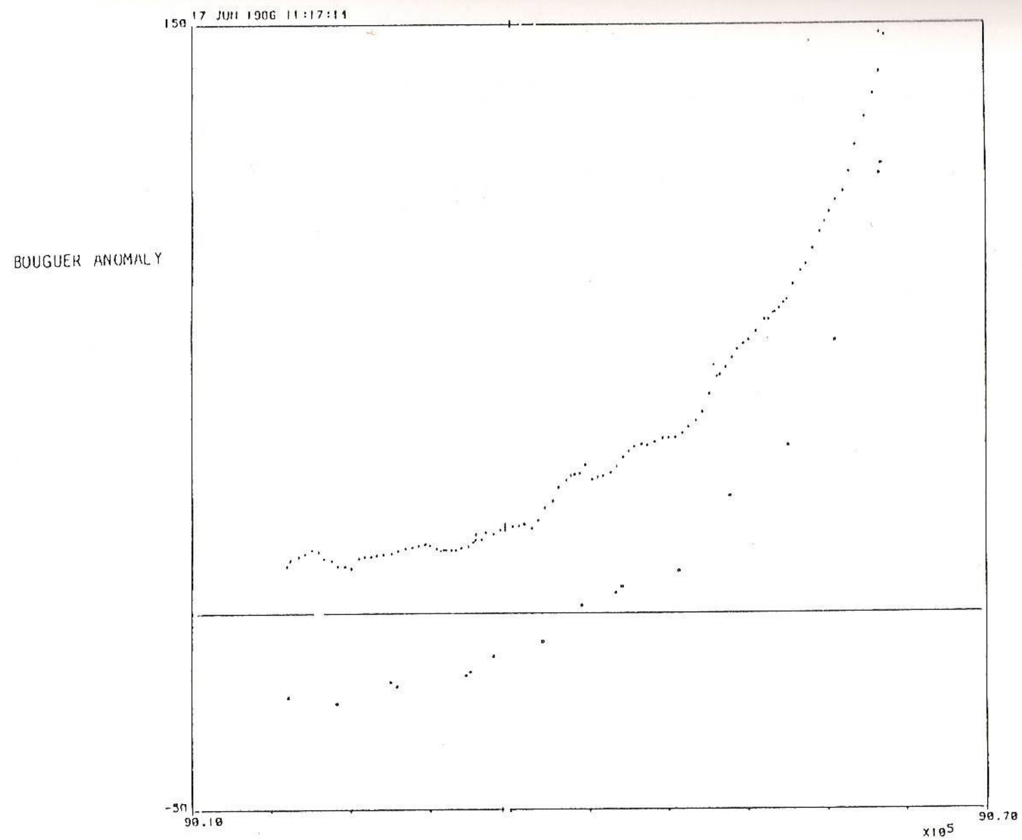
The method employed was to obtain an observed gravity value for each Shell station by working backwards through the normal set of gravity reductions from the given Bouguer anomaly value, using the Shell density value of 2.1 g/cc.

The normal set of gravity reductions:

Bouguer anomaly = observed gravity - latitude correction

+ free air correction - Bouguer correction

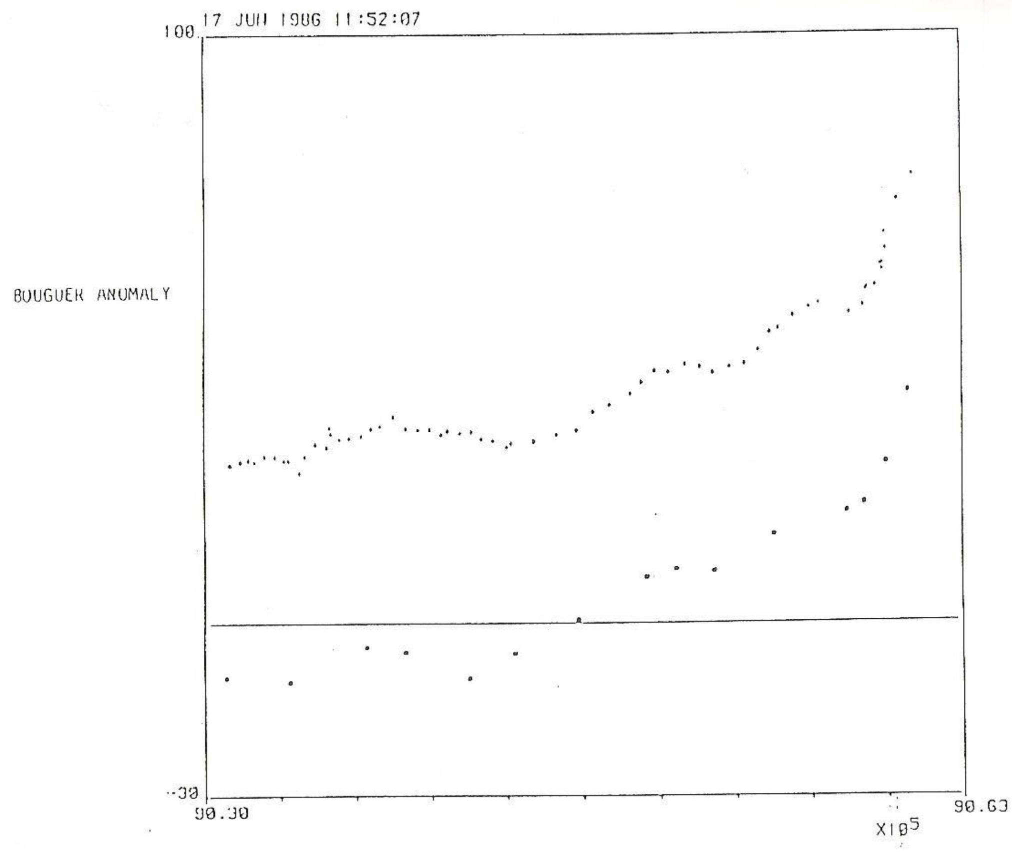
Having obtained an observed gravity value for each station a new Bouguer anomaly could be computed by using the same reduction steps but with the 1967 International Gravity Formula and a density value of 2.67 g/cc. The new Bouguer anomaly values were then computationally correct with respect to the IGSN71 International Gravity Network except for a datum shift due to Shell having set their original base Bouguer level to zero for station 33. This datum shift had to be determined and removed if the Shell survey was to be compatible with the present day gravity system. Chamalaun (Chamalaun,1976) assigned a value of -20 mGals to station 33 to bring the Shell survey values in line with his own survey. The value of station 33 after the above computations was +15 mGals while nearby stations from the Portuguese, Flinders University and Imperial College surveys had values close to -20 mGals. It appeared that -20 mGals was a reasonable value to set to station 33 which meant that all the Shell stations should be shifted by -35 mGals to bring them in line with IGSN71. However, a single station is not really sufficient to assess this datum shift and so data were also used from two roads north to south across the island along which there were sufficient Shell stations and corresponding Portuguese or university stations for the two data sets to be plotted and the datum shift to be graphically assessed (Figs.1.2.2.1.1 & 2). The Shell survey had a similar gradient to the control survey but the Bouguer anomaly values of all of the Shell stations were too high by some 35 mGals. With a datum shift of -35 mGal the Shell survey plotted close to the control survey (Figs.1.2.2.1.3 & 4). Least squares analysis was also carried out on the Shell and later datasets. For the road Baucau to Viqueque the standard deviation is 1.5mGal at the 95% confidence level following a -34mGal datum shift. This datum shift has been applied to all of the Shell data.



SHELL (+) AND PORTUGUESE PLUS UNIVERSITY (■) BOUGUER ANOMALIES PLOTTED AGAINST LATITUDE. ROAD BACAU TO VIQUEQUE.

FIGURE 1.2.2.1.1 Shell vs. Portuguese and University data.

No datum shift. Road Bacau to Viqueque.



SHELL(+) AND PORTUGUESE PLUS UNIVERSITY(■) BOUGUER ANOMALIES PLOTTED AGAINST LATITUDE. ROAD LAGA TO CAZABAU.

FIGURE 1.2.2.1.2 Shell vs. Portuguese and University data.

No datum shift. Road Laga to Cazabau.

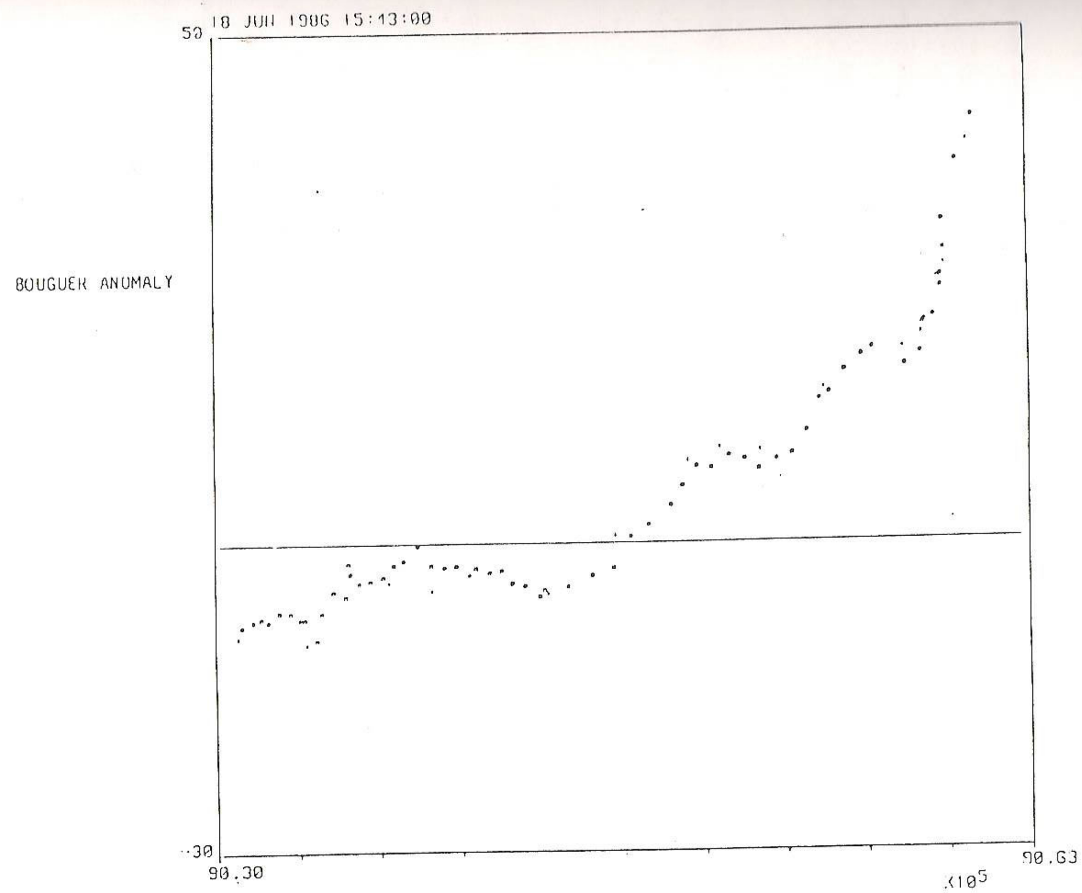


FIGURE 1.2.2.1.3 Shell vs. Portuguese and University data.

35mgal Shell datum shift applied.

Road Laga to Cazabau.

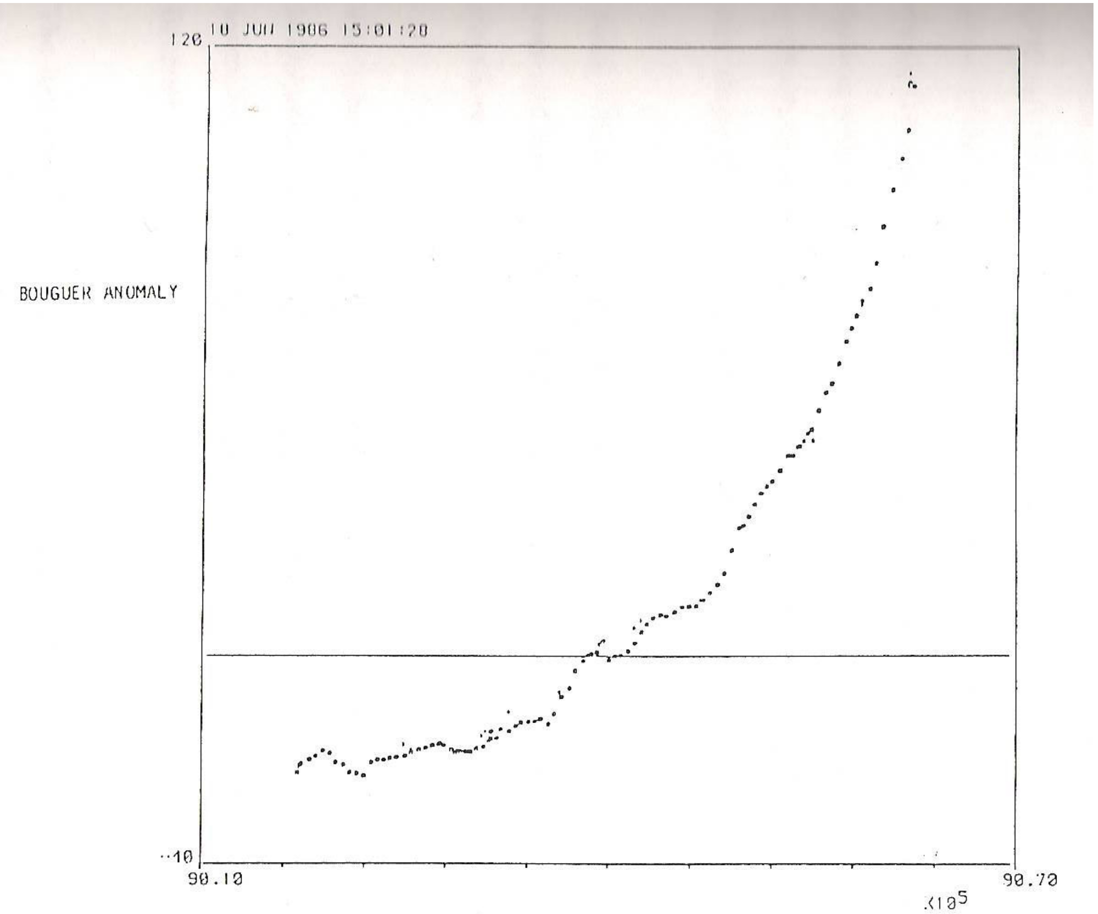


FIGURE 1.2.2.1.4 Shell vs. Portuguese and University data.

35mgal Shell datum shift applied.

Road Bacau to Viqueque.

1.2.2.2 TIMOR OIL DATA

The Timor Oil data set is the result of a number of individual surveys conducted between 1959 and 1962, concentrated in the south of East Timor (Fig.1.2.2.2). Timor Oil were aware of the earlier Shell survey and in fact incorporated Shell data in their study. The Timor Oil survey largely covered areas that the Shell survey did not but in some regions there is some overlap (compare Figs.1.2.2.1 & 2). Unfortunately Timor Oil only had maps of Shell's Bouguer anomaly values and so when incorporating Shell data into their survey they simply shifted the Shell datum to their own.

Timor Oil, in common with Shell, had no reliable large scale topographic maps to work from and had to carry out their own topographic survey to obtain station locations and elevations.

The Timor Oil survey data was available in the form of a copy of the original report by M.G.Audley-Charles, and a number of maps depicting station location and Bouguer anomalies. Two additional maps were available for the later 1962 survey again showing Bouguer anomaly values.

The locations of the stations were only available from the 1:40000 and 1:20000 scale Bouguer anomaly maps. A Grant Projector was used to copy the original maps and to reduce the scale to the 1:50000 of the Portuguese topographic maps. A method similar to that employed for relocating the Shell stations was used, whereby, the Grant Projector copies of stations were transcribed onto the draft-film copies of the topographic maps having already made reasonable relocations of the stations. The relocation process was based largely on the assessment of the position of individual stations forming strings along roads,rivers and the coastline. The reader is referred to section 1.2.2.1 describing the method used to relocate the Shell stations.

The Shell stations are believed to have been relocated to an accuracy of about 50m but due to the poor quality of the original Timor Oil maps the positioning of these latter stations are believed to be accurate to only 75-100m. Some stations at road junctions are positioned precisely but stations away from any junction are located with decreasing accuracy the further from the junction. Less accuracy is inevitable in the relocation of stations not on roads or rivers. Known station heights were compared to the elevations shown on the Portuguese topographic maps.

After relocating and plotting the stations on the draft-film copies, the locations were digitised and output in Universal Transverse Mercator (UTM) coordinates. The digitising process is explained in greater detail in section 1.2.2.6.

The next step involved calculating new Bouguer anomaly values using the 1967 International Gravity Formula and tying these to the IGSN71 International Gravity Network. Locations, elevations and observed gravities were required for each station. Unfortunately, not all the data sets in the Timor Oil survey had observed gravity values and/or elevations (Table 1.2.2.2).

SURVEY	OBSERVED GRAV.	ELEVATION	BOUGUER ANOM.
1959 Suai survey	yes	yes	yes
1959 Viqueque survey	yes	yes	yes
Mines Administration	yes	no	yes
Timor Oil 1962 survey	no	no	yes

Table 1.2.2.2

Of the four, only the Suai and Viqueque surveys had all the data required for adjustment to the present day gravity system. The method used for these data sets is similar to that employed for the Shell data except that an observed gravity value did not have to be retrieved. The Suai and Viqueque observed gravity values were used with the 1967 International Gravity Formula to compute new Bouguer anomaly values.

For the Timor Oil 1962 survey observed gravity values had to be back-calculated. Elevations were taken from the Portuguese topographic maps, contoured at 25m intervals with numerous spot heights. The accuracy of the elevations depends on the terrain gradient; if gentle, as near the coast, values are accurate to 1m, but where gradients are steep they are accurate to within 5m, except in the vicinity of spot heights where accuracy is up to 1-2m. Having acquired the elevation the observed gravity value for each station could be retrieved in a similar manner to that employed for the Shell data. (cf. section 1.2.2.1)

Mines Administration, a firm based in Brisbane, was contracted by Timor Oil to conduct a gravity survey. Elevation values for this survey were estimated from the Portuguese topographic maps. New Bouguer anomaly values were computed using the 1967 International Gravity Formula.

At this stage all stations for the Timor Oil survey were compatible with the 1967 International Gravity Formula and consequently the Portuguese and University surveys. In addition all the values had been computed with a standard density of 2.67 g/cc and to a standard elevation datum, namely the datum set up by the Portuguese for their topographic maps.

However, as with the Shell survey, there was an unknown gravity datum shift in the Timor Oil data which meant that it was not compatible with the International Gravity Network IGSN71. It was known that the values were too high for any one locality but not by how much. It was decided to again employ the graphical method for determining this datum shift, as had been done for the Shell survey.

The road between Suai and Hatudo, running west to east on the southern coastal plain, was chosen as there are sufficient Portuguese stations along this road to give control. On plotting out the Timor Oil and Portuguese Bouguer anomalies against longitude it was discovered that the gradients of the two surveys matched each other fairly well but that there was a datum shift of between 48 mGal and 51.5 mGal. Initially, a 50mGal datum shift was applied to the Timor Oil anomalies which resulted in a close correspondence with the Portuguese anomalies (Fig.1.2.2.2.1). Finally, least squares analysis was conducted on two Timor Oil datasets to determine more accurately the required datum shifts. One required a datum shift of -38mGal, giving a standard deviation of 2.9mGal at the 95% confidence level, while the other needed a -49mGal shift, resulting in a standard deviation of 1.9mGal at the 95% confidence level.

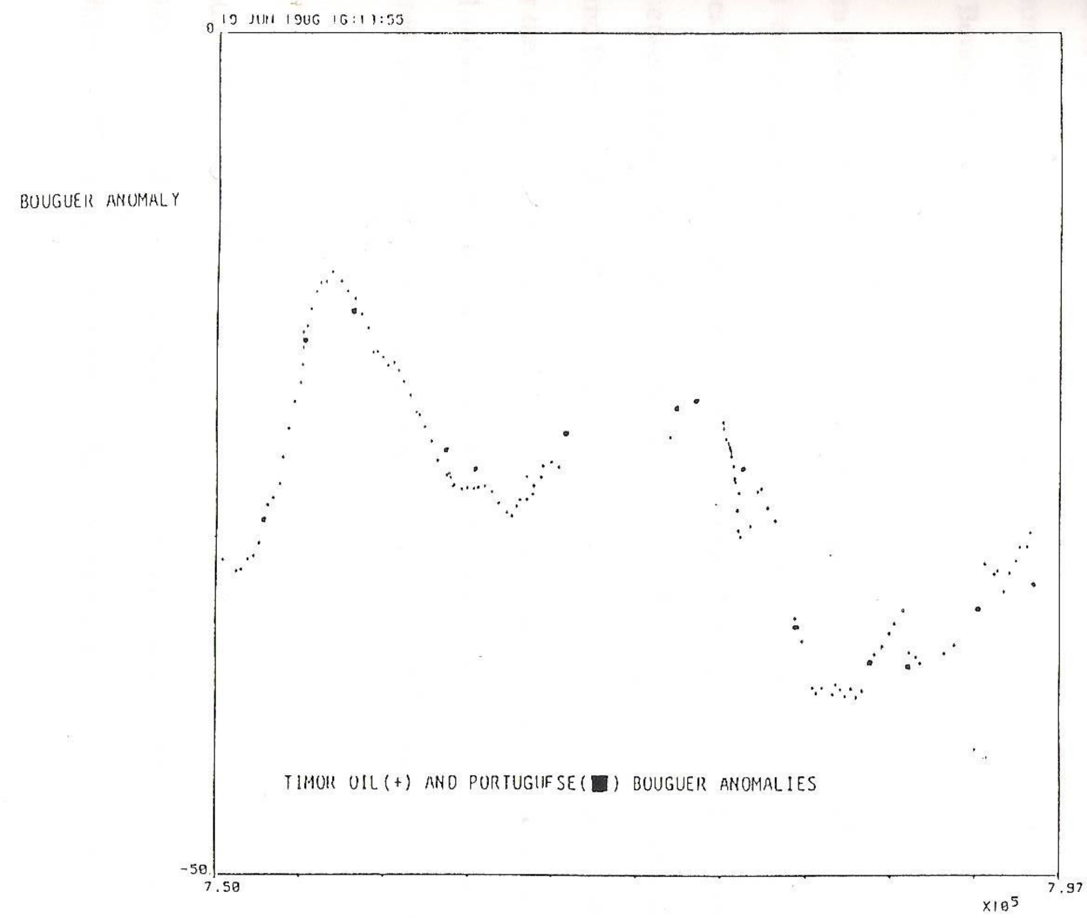


FIGURE 1.2.2.2.1 Timor Oil vs. Portuguese data. 50mgal Timor Oil datum shift applied. Road Suai to Hatudo.

1.2.2.3 FLINDERS UNIVERSITY SURVEY

In August 1973 a detailed gravity traverse was carried out across East Timor by workers from Flinders University of South Australia (Chamalaun,1976). The team were interested in the strong north to south gravity gradient of Timor and so surveyed from Dili in the north to Betano in the south.

A Worden Pioneer gravimeter was used at stations generally less than 1500m apart and drift was corrected by looping an ABABCB... pattern. The reported error in gravity differences between successive stations was less than 0.03 mGal and the overall loop closure between Betano and Dili was less than 0.5 mGal. A gravity tie made between Baucau and Darwin (on the IGSN71 system) and between Baucau and Dili gives 978227.36 mGal for the Dili Airport station MGT 1956. This station was set as the 0mGal datum to which all other survey stations were tied. The resulting gravity differences have been recalculated using the 1967 gravity formula, a density of 2.67g/cc, and tied to IGSN71 at Darwin.

The Flinders survey was the first to make use of the 1:50000 Portuguese topographical maps published in 1967. Stations were located on the maps to within 50m and elevations were estimated either from MGT precision level bench marks or barometrically.

Flinders stations were transcribed onto the draft-film copies of the topographic maps. There was no requirement for this step, but it was felt that the copying and digitising of these stations, would act as a control on the Shell and Timor Oil surveys.

1.2.2.4 IMPERIAL COLLEGE SURVEY

The second survey to be conducted in the 1970's was by A.R.Richardson in August 1974 (Milsom and Richardson,1976). It was also the second survey in this study to have the benefit of the Portuguese topographic maps, the 1967 International Gravity Formula and of ties to IGSN71.

Again, the survey was primarily concerned with the strong north to south gravity gradient across Timor. To this end two traverses were conducted from Dili in the north to Same in the south and from Baucau south to Viqueque, the two traverses being linked in the north along the Dili to Baucau road (Fig.1.2.2.3).

Elevations were gained from the Missao Geografica de Timor (MGT) precision level bench marks and elsewhere by barometric measurement. The MGT derived elevations are accurate to within a few centimetres. Station coordinates were estimated from the Portuguese topographic maps.

Gravity measurements were by a LaCoste Romberg geodetic meter (G90). Absolute values were obtained by reference to the survey pillar MGT 1956 at Dili Airport, which had already been tied to the Australian Government base in Darwin, part of the IGSN71 system (Chamalaun et al,1976). This gives a value of 978227.36 mGals for MGT 1956 and ties the Imperial College survey with the Flinders University survey.

When the stations were plotted, using the Benson, and compared with the Portuguese maps it was discovered that there were errors in the location of a few stations. For this reason, and also to give some control over the relocation method employed on the Shell and Timor Oil surveys, the Imperial College stations were relocated onto the draft-film copies of the topographic maps and digitised.

Bouguer anomalies were computed using the digitised station location latitudes and a density of 2.67 g/cc.

1.2.2.5 PORTUGUESE SURVEY - MISSAO GEOGRAFICA DE TIMOR

The results of the Portuguese survey were published in 1978 (Botelho,1978) following many years of work. In 1954 the Missao Geografica de Timor (MGT) was organised with a brief to produce a series of 1:50000 scale maps and to conduct a gravity survey of East Timor (then Portuguese Timor). Work began on the gravity survey in 1966 after the completion of the surveying for the maps and the setting up of the precision level bench marks, and was completed in December 1973.

The survey made use of a Worden geodesic gravimeter, values being tied to the IGSN71 station at Darwin,Australia and Baucau Airport. The gravity datum at Baucau Airport was then tied to Dili and Atauro airports.

Naturally, use was made of the MGT levelled system for location and elevation control of stations. Elevations are published to the nearest centimetre but latitudes and longitudes only to the nearest tenth of a minute (approx. 200m).

The published results (Botelho,1978) include observed gravity, normal gravity and a Bouguer anomaly for each station. However, small variations in the constants for determining the latitude correction and the free air correction, together with a density value of 2.6 g/cc rather than 2.67 g/cc necessitated the computation of a new Bouguer anomaly. This brings the Bouguer anomaly values for the Portuguese survey in line with all the other surveys in this study.

1.2.2.6 THE DIGITISING PROCESS

As already mentioned the Shell, Timor Oil, Flinders University and Imperial College stations were plotted onto the draft-film copies of the Portuguese topographic maps, after due allowance had been made for their true locations with respect to features on the topographic maps.

Each draft-film copy was digitised using a global transformation into Universal Transverse Mercator coordinates (UTM). The global transformation allowed all 37 maps to be digitised and to retain their correct position relative to each other when plotted out. The UTM system is particularly useful because the rectangular coordinate system removes the possibility of projection abberation when using rectangular plotters such as the Benson. However, latitudes for each station were required for the latitude correction via the 1967 International Gravity Formula, and a program was modified to convert the large data sets from UTM to latitude and longitude.

The coastline and land border of East Timor were digitised, each point being separated by approximately 350m on the ground. Where necessary, the distance between points was decreased to enable the finer points of the coast to be portrayed. An identical global transformation to that employed for the digitising of the stations was used, enabling the plotting of both gravity stations and coastline using the same coordinate reference system.

1.2.3 WEST TIMOR LAND DATA

West Timor was surveyed by the Geological Research and Development Centre, Bandung (GRDC) between 1977-79, using a LaCoste Romberg gravimeter. Elevations were recorded by Paulin altimeters, controlled by reference to sea-level and known airport heights. Elevation errors may be as much as 10m, which corresponds to about +/-2mGal of Bouguer anomaly at a density of 2.67g/cc. Full terrain corrections have not been carried out. The survey is tied to the Indonesian National Gravity Base Network (Adkins et al,1978) and so to IGSN71. Station distribution (386 stations) is broadly similar to the Portuguese survey of East Timor giving regional coverage of the whole of Timor (see Map 1, rear pocket).

The new Timor Bouguer anomaly map reproduces the contours for most of West Timor shown on the GRDC preliminary Bouguer anomaly map (Simamora and Untung, 1983). Variations from the GRDC map occur where the original east and west maps were joined. For contour values above zero milligals there was an almost complete match, however, at lower values adjacent to the border the contours had to be redrawn.

The former political enclave of Ocussi, on the north coast of West Timor, together with the island of Atuaro were administered by the Portuguese government of East Timor. Consequently, both areas were surveyed by MGT. In Ocussi the MGT data was easily matched with that of GRDC, with contours flowing along strike from one region to the other.

1.2.4 MARINE DATA

Data from two marine cruises (Fig.1.2.4.1) have been used to control the contours in the Wetar Strait and along the north coast of West Timor. The earlier of the two was the Scripps Institution of Oceanography RAMA12 expedition by the R/V Thomas Washington in 1981. The second was by the R.R.S. Charles Darwin (National Environmental Research Council) in 1988. A total of approximately 3500 data points have been used.

Bouguer anomalies were produced by replacing sea-water with rock of density 2.67g/cc. There are six cross-overs of the two data sets with discrepencies in the range 2-5 milligals probably due to errors in the positioning of the earlier Thomas Washington cruise. The Charles Darwin cruise in 1988 made use of the Global Positioning System which is far more accurate than the navigation systems previously available in this area.

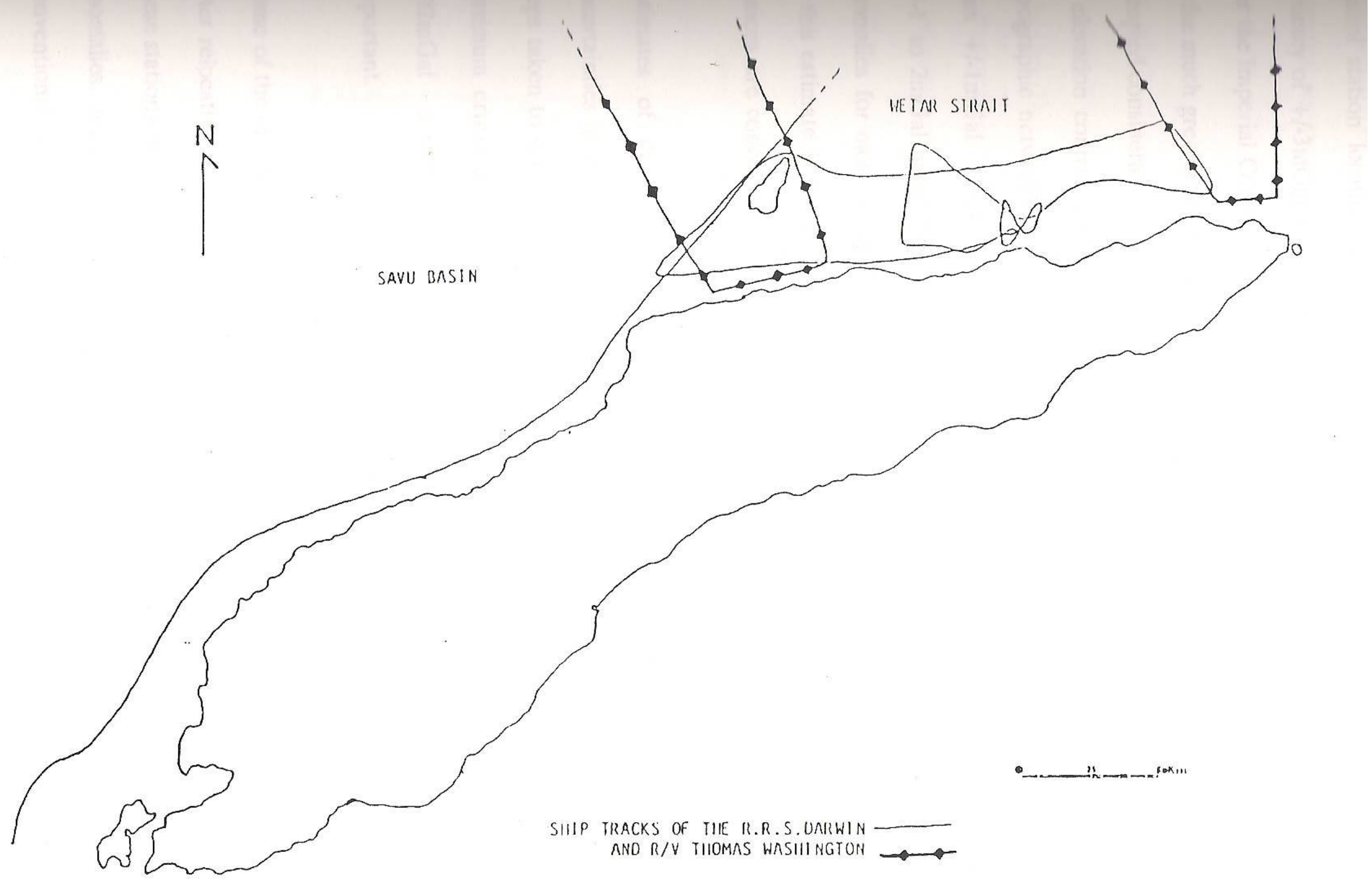


FIGURE 1.2.4.1 Ship track chart

1.2.5 ERRORS IN THE COMPUTATION OF THE BOUGUER ANOMALIES.

The Flinders University, Imperial College and Missao Geografico surveys of East Timor all made use of the Portuguese 1:50,000 topographic maps and associated benchmarks to control station location and height estimates. Chamalaun (1976) estimates an overall accuracy of +/-3mGal for his Bouguer anomalies, while Milsom (pers. comm.) considers that the Imperial College anomaly values are accurate to +/-1mGal. The difference is due to the much greater reliance on barometric levelling by the Flinders University team, who occupied considerably more stations; Bouguer anomaly errors are classically due to errors in elevation control. As the Missao Geografico survey also made extensive use of the topographic network, their anomaly values are estimated to also be equal to, or better than, +/-1mGal. The GRDC (1983) survey of West Timor has an estimated accuracy of +/-1 to 2mGal based on the +/-10m maximum error in elevation. Therefore, Bouguer anomalies for most of Timor are probably better than +/-3mGal overall. The exception to this estimate is the south coast of East Timor where the Shell and Timor Oil surveys stations are concentrated.

Estimates of the accuracies of the Shell and Timor Oil surveys are plagued by uncertainties in the accuracy of the original survey and the guesswork involved in some of steps taken to correct, or retrieve, the original data. If stations have been relocated with maximum errors of +/-100m then the maximum theoretical latitudinal gravity change is 0.02mGal - a value too low to be significant. Errors in elevation may be much more important.

Some of the original Timor Oil station elevations have been lost and had to be estimated after relocating the stations by reading heights from the 1:50,000 topographic maps. For these stations the maximum elevation error is estimated to be +/-1 to 2mGal for Bouguer anomalies. All other elevations for the Shell and Timor Oil surveys were obtained by conventional topographic survey and may have had an original accuracy equivalent to +/-0.1mGal Bouguer anomaly.

Any remaining error in the Shell and Timor Oil surveys is due to the datum shift that was required to make these surveys compatible with the present-day gravity system. Besides a graphical comparison of Shell and Timor Oil Bouguer values with later surveys, regression analyses were also carried out. The minimum and maximum standard deviations are 1.5 and 2.9mGal for a number of datasets.

The errors in positioning, height control and datum shifts are thought to produce maximum error in the Shell and Timor Oil Bouguer anomaly values of approximately +/-4 to 5mGal. The effect of this error is mitigated by the 10mGal contour interval used on the Bouguer anomaly map. It must also be noted that this error will be largely systematic, i.e. the relative error between any two Shell or Timor Oil surveys will probably be less than a milligal.

CHAPTER 1.3

BOUGUER ANOMALY MAP OF THE TIMOR REGION

1.3.1 TIMOR

The most obvious feature of the Bouguer anomaly map (Map 1,rear pocket) is the very steep, positive gradient south to north across Timor, starting from approximately -50mGal on the south coast and rising to +150 to 160mGal in the north. Also striking are the large left-lateral offsets in the anomaly field. These features are best discussed in conjunction with the known geology of the island.

On map 2 (rear pocket) the Bouguer anomaly contours and geology have been combined. The autochthonous middle Pliocene to Recent deposits have been omitted to aid clarity. Also not shown is the distribution of the Bobonaro Scaly Clay which, although almost ubiquitous, is still the subject of controversy concerning the mode and timing of emplacement. The Bobonaro is classified as either originally an olistrostrome deposit or the result of considerable shale diapirism due to the collision process. This unit has a low density and where it is clearly 'blanketing' earlier units, as in most of the northern half of Timor, it will be discounted when considering the anomaly field. In southern Timor, localised lows of -45mGal to -70mGal occur which may be due to basins infilled with Bobonaro Scaly Clay, or erosional products from this unit. One on-shore well drilled near to the south coast of East Timor encountered 2000m of Bobonaro. However, the Bobonaro will have a similar density to autochthonous molasse units and so the distinction between them on gravitational grounds cannot be made.

Broadly speaking the para-autochthonous and autochthonous areas in southern Timor are characterised by Bouguer anomaly values in the -70 to -10mGal range. In these areas the regional anomaly field decreases from -10mGal in the north to approximately -45mGal in the south (Map 1,rear pocket). Superimposed are localised lows which are probably due to small, molasse-filled, basins formed in the older para-autochthonous units. In East Timor these lows are not extensive or numerous but the opposite is true in West Timor. There the Central Valley is characterised by low anomaly values and steeper gradients than any comparable area in East Timor. Four distinct lows can be identified either within or adjacent to the Central Valley (see Fig.1.3.1.1).

All four are in areas where both para-autochthonous and autochthonous rocks outcrop. It should be noted that low 1, some 20km south-east of Halilulik, is based on one gravity station with a value of around -30mGal. The station might be sited on a high peak and the low might be removed by applying a full terrain correction.

All the other lows are controlled by a number of stations in regions of low elevation and are considered genuine. Lows 2,3 and 4 (Fig.1.3.1.1) are situated on the southern flank of the Central Valley where there are extensive outcrops of autochthonous rocks, particularly the Noele and Batuputih Formations. Low 2 does not appear to be strongly associated with any recent alluvial deposits and is certainly offset to the south of the present river systems that flow through the Central Valley. However, lows 3 and 4 are centred on river valleys where there is present-day alluvial deposition. Both lows show a roughly NNE to SSW trend which matches the flow of rivers away from the Central Valley to the south coast. This is particularly noticeable in the case of low 4, lowest anomaly value being reached at the confluence of major river systems some 40km to the east of Camplong (Fig.1.3.1.1). Additionally, gradients at the margins of lows 3 and 4 are very steep, suggesting fault-bounded grabens, orientated NNE-SSW, which have been infilled with autochthonous molasse deposits (and possibly Bobonaro Scaly Clay). These grabens have controlled the river systems in West Timor for some time. Both lows extend off-shore to the south suggesting that thick estuarine deposits exist there. Low 4 at -70mGal has an anomaly value equivalent to 4.5 km of sediment at a density contrast of 0.4g/cc.

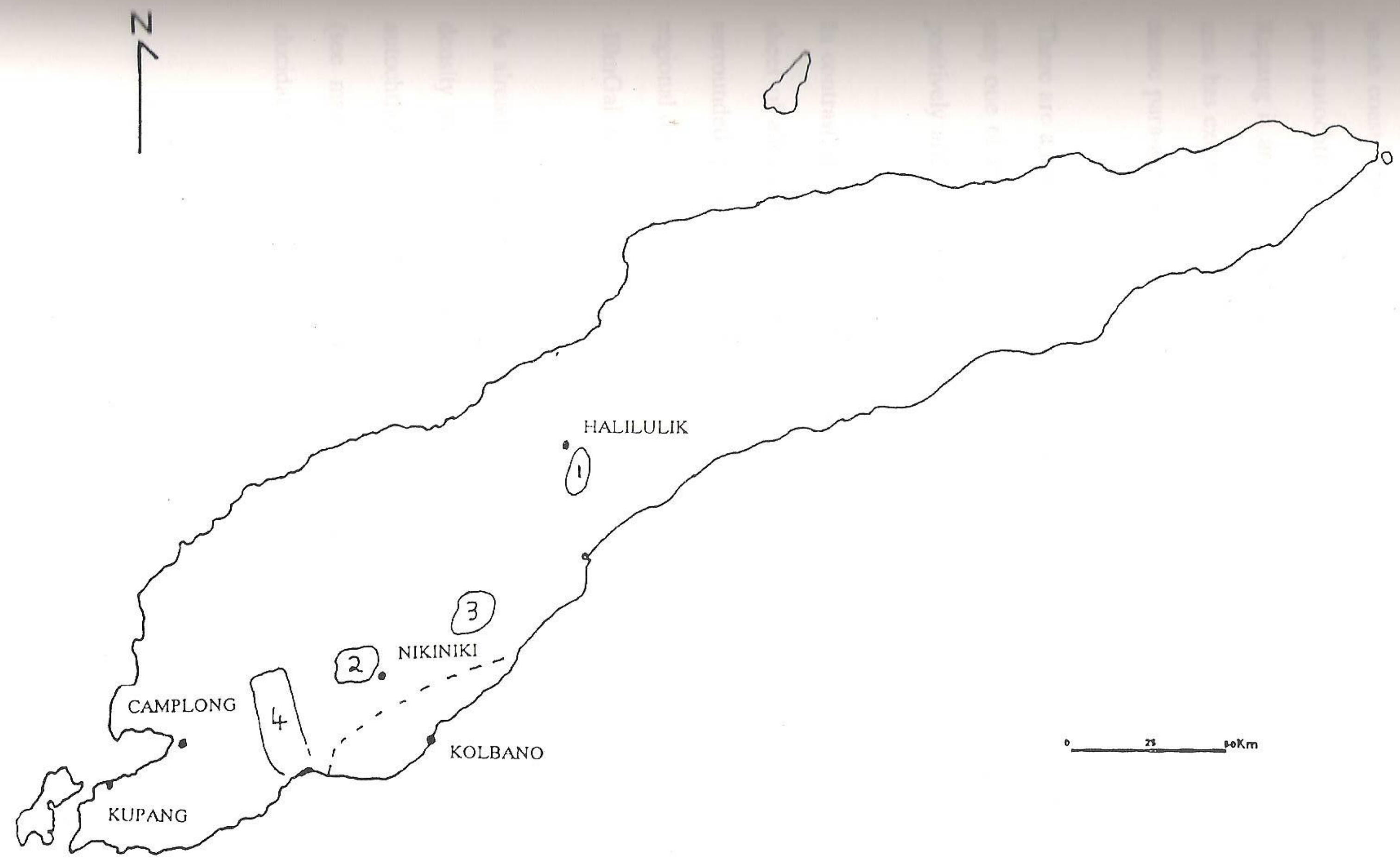


FIGURE 1.3.1.1 Bouguer anomaly lows of West Timor

Anomaly values in the southern coastal regions of West Timor are generally higher than those in the Central Valley and consequently anomaly gradients are positive towards the south coast. This is especially true for the Kolbano region (Fig.1.3.1.1) where Australian para-autochthonous units have been imbricated and stacked. South of Camplong and Kupang is an area of similar anomaly values and gradients to the Kolbano region. The area has extensive surface outcrops of Bobonaro Scaly Clay and recent deposits but more dense para-autochthonous rocks probably underlie this cover.

There are a few scattered outcrops of allochthonous rocks in the south of West Timor but only one of the Maubisse Formation situated 40km south-east of Nikiniki (Fig.1.3.1.1) positively affects the local anomaly field.

In contrast, near the town of Lolotoi in East Timor (Fig.1.3.1.2) there is a large thrust sheet of allochthonous material made up of Lolotoi, Dartollo and Cablac Formations, surrounded by para-autochthonous and autochthonous units. This sheet reverses the regional decrease in Bouguer anomalies towards the south coast, with values increasing to -10mGal at the centre of the thrust sheet.

As already mentioned, the north of Timor is characterised by the presence of medium density allochthonous rocks, the majority of which form thrust sheets on top of para-autochthonous material. In some northern areas only para-autochthonous units outcrop (see map 2, rear pocket and Fig.1.3.1.3). These areas (P1 to P4) are important in elucidating the tectonic development of Timor and will now be discussed in detail.

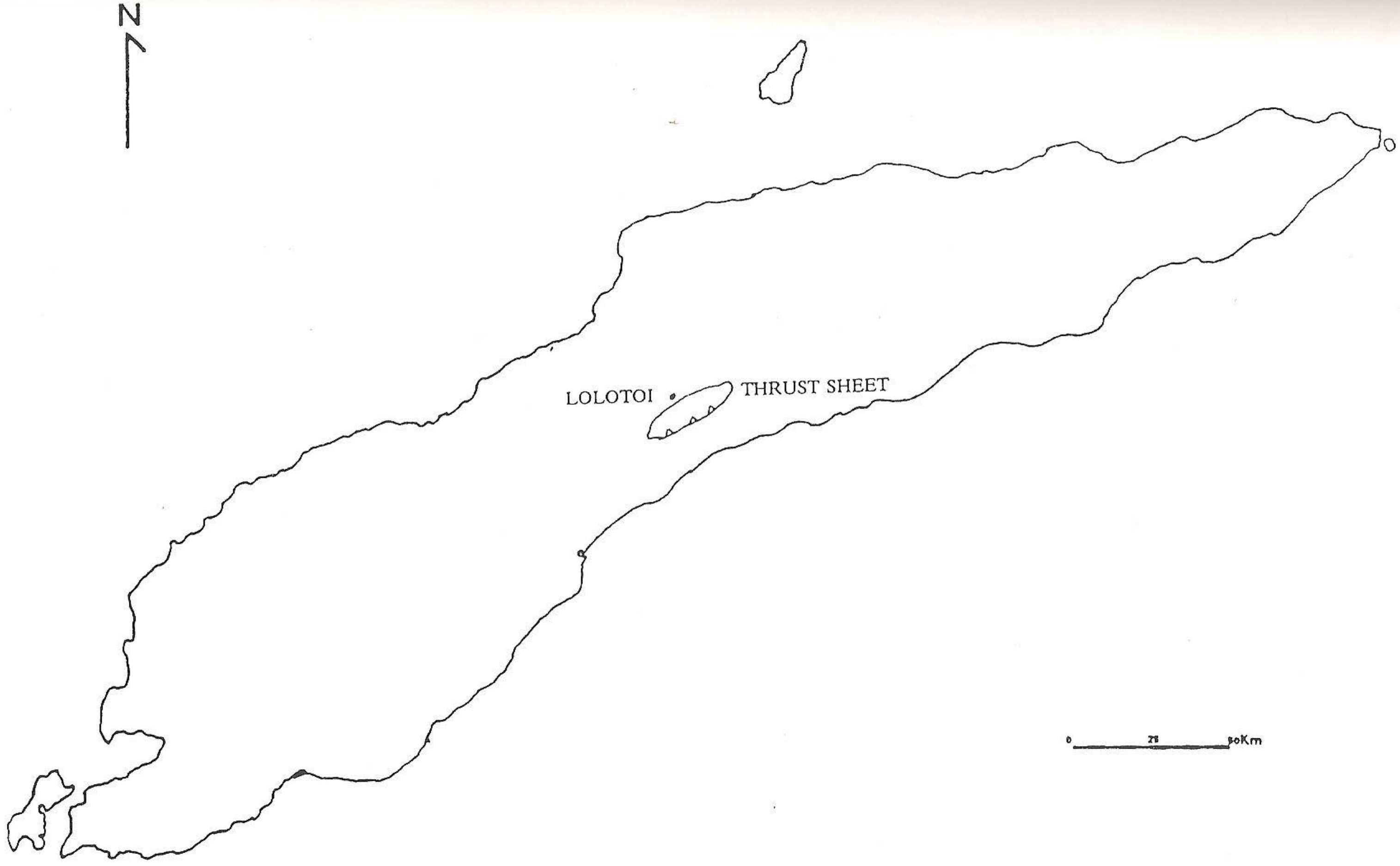


FIGURE 1.3.1.2 The Lolotoi nappe of East Timor

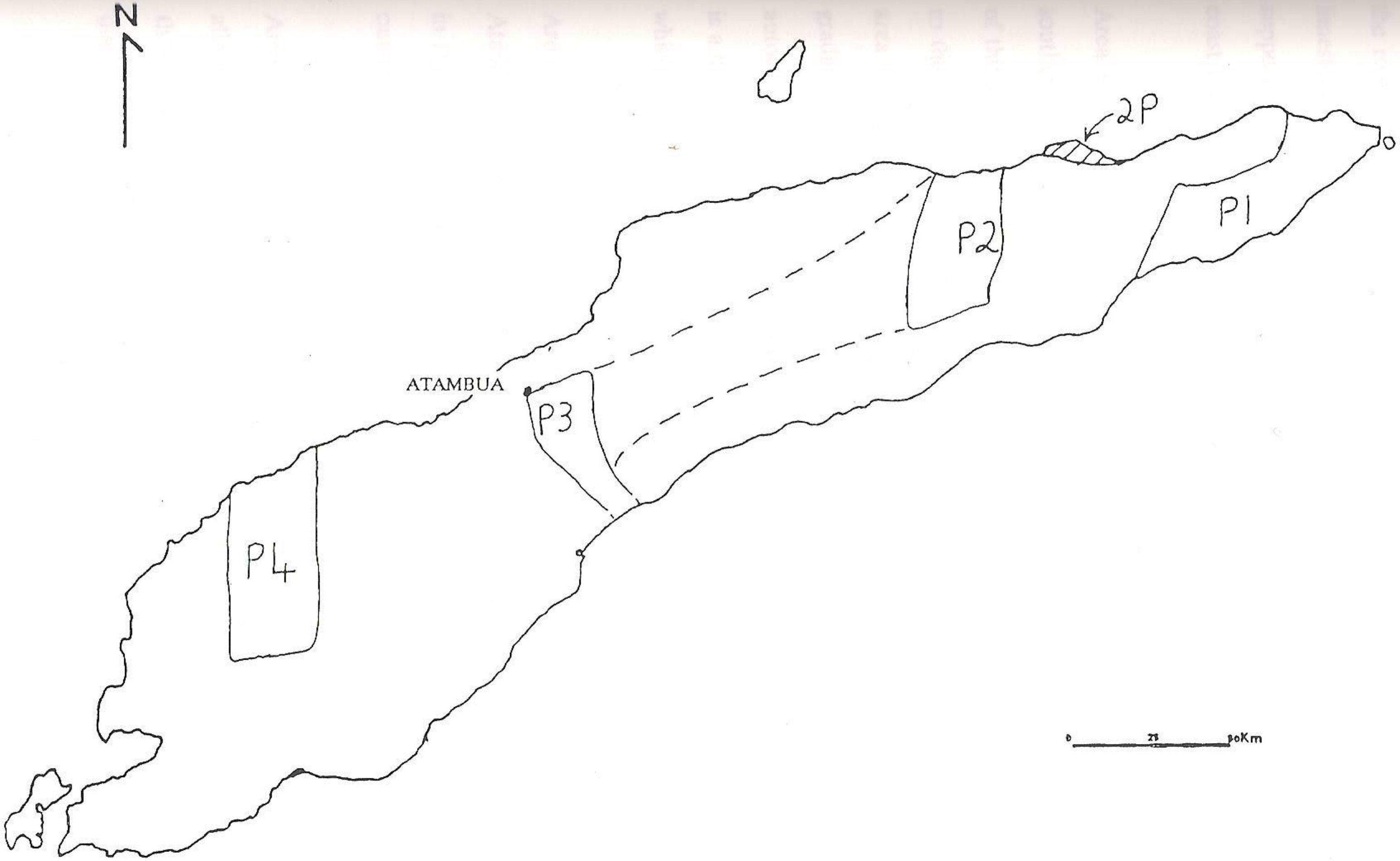


FIGURE 1.3.1.3 Para-autochthonous areas of Timor

Area P1 (Fig.1.3.1.3) consists almost entirely of para-autochthonous units and this is reflected in the anomaly field by the northwards displacement of the negative portion of the regional gradient. To the north of area P1 is a region occupied by autochthonous limestones and lacustrine deposits which probably overlie the para-autochthon. This supposition is supported by relatively low Bouguer anomaly values attained on the north coast (50 to 100mGal), and the presence of para-autochthonous units there.

Area P2 (Fig.1.3.1.3) is a corridor of para-autochthonous material that extends from southern Timor to the north coast and is flanked, in outcrop, by allochthonous units. West of this area, para-autochthonous units extend beneath allochthonous nappes all the way to the eastern flank of area P3 in West Timor (Fig.1.3.1.3). Immediately to the west of area P2 is a large thrusted sheet of Lolotoi Formation allochthonous rock. The anomaly gradients to the east of area P2 suggest that here also the para-autochthon is overlain by autochthonous molasse and Bobonaro Scaly Clay. Some 35km to the east of area P2 there is a large left-lateral offset in the anomaly field suggesting a major lithological disjunction which cuts across Timor trending NNE-SSW.

Area P3, in the middle of Timor, can be traced from the south coast as far north as Atambua (Fig.1.3.1.3). Once again the Bouguer anomaly contours are offset to the north in this region due to the presence of the para-autochthon. There are small and localised outcrops of allochthonous rocks but they do not greatly affect the overall anomaly trend.

Area P4 (Fig.1.3.1.3) is another para-autochthonous dominated area in which few allochthonous rocks outcrop. Again, anomaly contours are offset to the north. However, there are relatively few gravity stations in this region and so finer details are not discernable.

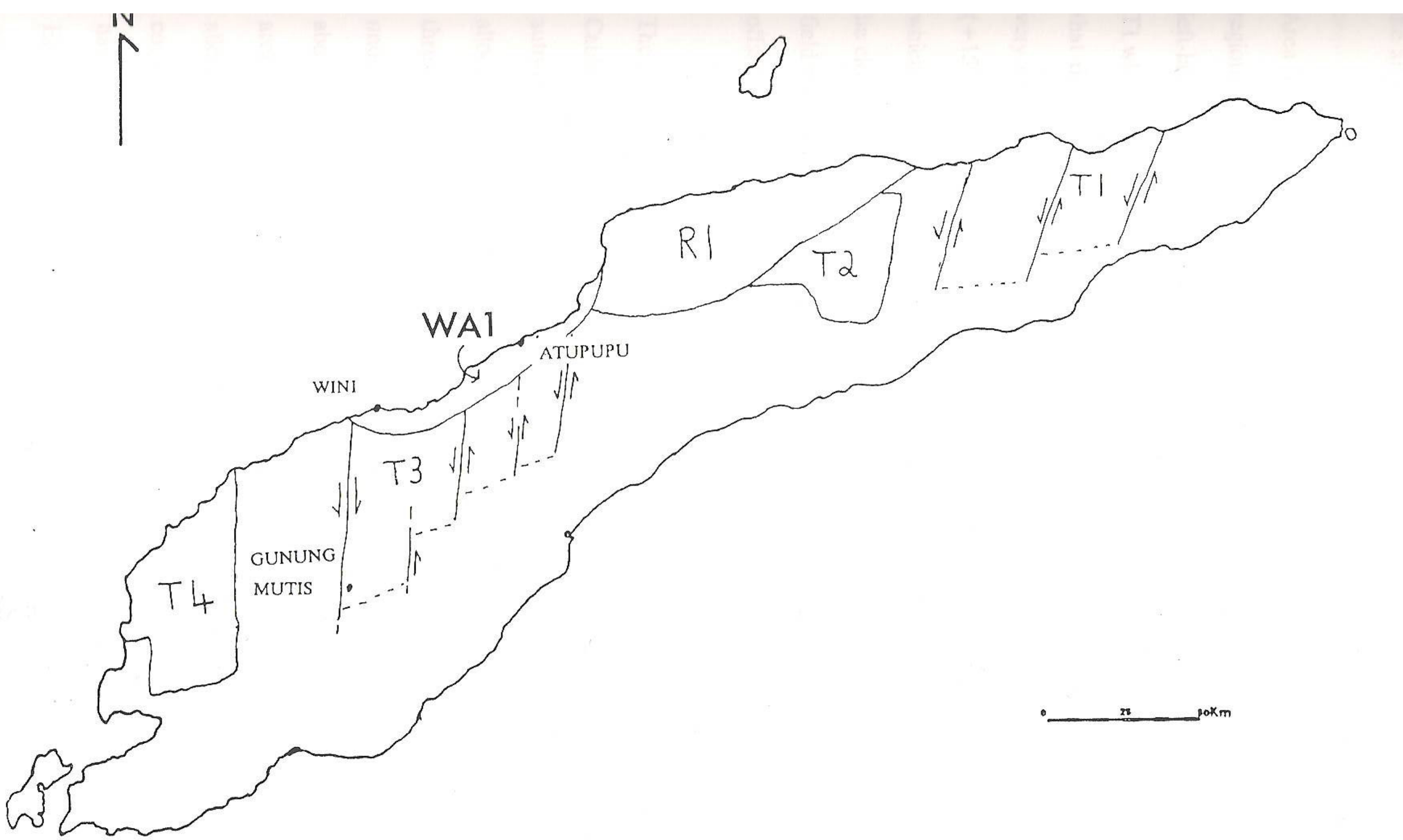


FIGURE 1.3.1.4 Allochthonous areas of Timor

Having discussed the para-autochthonous areas in northern Timor we will now consider the allochthonous regions of Timor marked on Fig.1.3.1.4.

Area T1 (Fig.1.3.1.4) is a region bordered to the east and west by para-autochthonous regions and separated from them by faults marked on the geological map and by major left-lateral offsets in the Bouguer anomaly field. There is also an offset in the middle of T1 which can be followed across the width of Timor. Study of the anomaly field indicates that the middle offset effectively splits the area T1 in two, with the western side having very much higher anomaly values at the north coast than the eastern. These high values (+150mGal) and steep gradients in the north west of T1 are not matched by the geology which consists of autochthonous Baucau Limestone (raised coral reef). Denser units must lie close to the surface and these are interpreted as part of the volcanic arc. The anomaly field does not support this interpretation in the eastern half of T1, but here the left-lateral offsets imply a northwards movement of the east relative to the west.

The geological units outcropping in area T1 are mostly allochthonous Lolotoi, Barique and Cablac Formations with a few nappes of Maubisse Formation at the margin. Para-autochthonous rocks do outcrop throughout the area and are in places adjacent to the allochthonous units. The anomaly field for most of the area is indicative of allochthonous thrust sheets overlying para-autochthonous units. This implies that the para-autochthon underlies most of the area except for the north-west coastal quadrant, already discussed above. In essence therefore, the main difference between area T1 and para-autochthonous areas P1 and P2 (Fig.1.3.1.3), which border T1 to the east and west, is the presence of the allochthonous sheets. It is clear from the geological map, study of Landsat images, consideration of the local topography and the Bouguer anomaly field that these sheets have now been disrupted by the large offsets, by later normal faulting and by erosion. Erosion rates are rapid and it is probable that the thrust sheets were originally more extensive.

Area T2 (Fig.1.3.1.4) differs from all the other allochthonous regions in apparently still having complete thrust sheets in place. However, only reconnaissance field mapping has been carried out in this area. The presence of the Lolotoi thrust sheet overlying the para-autochthonous units has created a +15mGal rise in the background anomaly field. The same effect can be modelled elsewhere in southern Timor. It is these areas that most clearly indicate the thrusted nature of the Lolotoi, Barique, Maubisse and Cablac Formations (see section 1.4.2).

Area T3 (Fig.1.3.1.4) in West Timor is very similar to area T1 in East Timor except that in the west the anomaly gradient is much steeper, has considerable sinuosity and the width, north to south, is much less. Broadly speaking the same features are evident in T3 as they are in T1, i.e. left-lateral offsets and allochthonous sheets overlying para-autochthonous units. The western margin of T3 is fault-bounded against the para-autochthonous P4 area resulting in a right-lateral offset in the Bouguer anomaly field.

Allochthonous area T4 (Fig.1.3.1.4), in the west of West Timor is similar to T3 and T1. The boundary of T4 is roughly followed by the 0 mGal contour which runs parallel to the long axis of the island across para-autochthonous P4 (Fig.1.3.1.3), before turning sharply south at the margin with T4. The roughly north-south contour trend continues as far as Camplong (Fig.1.3.1.3) before turning sharply west again. This total offset, north to south, of some 60km in the regional field can be attributed to a large thrust sheet of Lolotoi and associated allochthonous units in area T4. On the geological map only a few localised outcrops of allochthonous rocks are marked but M.G.Audley-Charles (pers.com.,1988) reports that in road cuttings and deep valleys Lolotoi units outcrop in much of this region. Once again, para-autochthonous units are intermingled with the allochthon in outcrop, indicating the thrusted nature of the allochthon. On the west coast, bordering area T4, para-autochthonous units are found and the anomaly field decreases.

A few general points regarding areas T1-4 (Fig.1.3.1.4) are worth mentioning. Firstly, throughout Timor, wherever allochthonous units occur, they are commonly bordered to the north by para-autochthonous rocks and to the south by autochthonous molasse. This may be a result of the north to south negative topographic gradient across Timor, the effect of nappe emplacement from the north and the erosion of the topographically elevated allochthonous units, from which detritus would follow the regional topographic slope.

Secondly, all areas have extensive outcrops of the Bobonaro Scaly Clay and the anomaly field suggests that this unit is masking the presence of denser para-autochthonous and allochthonous units. Also the Bobonaro varies in thickness across the island and this factor does alter the steepness of local anomaly gradients. There are three important factors controlling local gradients: - 1) the thickness of autochthonous molasse units and Bobonaro overlying allochthonous sheets; 2) the thickness and depth of the hidden dense sheets; 3) the distance the area under consideration is from the very much denser rock in the Wetar Strait that is responsible for the steep, positive, regional gradient across Timor. These three factors are interdependent and until detailed geological knowledge is gained for any area, any local gravity modelling would be plagued by the usual ambiguity of the method.

The third general point concerns the distribution and affinities of allochthonous units in the various areas. Area T1 (Fig.1.3.1.4) is characterised by Lolotoi, Barique (and West Timor equivalents), Cablac Formations and a few outcrops of Maubisse Formation limestone. This contrasts with T3, where the Cablac Formation is rare except along the western margin where there are considerable outcrops of Maubisse. These variations suggest that there were considerable differences in the size and elevation of the T1-4 allochthonous regions prior to and during collision. The Early Miocene Cablac Formation is a massive, reefal limestone presumably deposited on elevated Lolotoi and Maubisse blocks. Therefore area T3 was presumably either elevated above sea-level, or water-depth was too great for reef formation.

Additionally, the variable distribution of the Maubisse Formation indicates that there were lithological and structural differences between the different blocks that initially collided with the earlier Banda Arc subduction zone. These differences were probably related to the Palaeozoic and Mesozoic history of the Australian continental shelf.

The fourth general point concerns the apparently intact allochthonous Lolotoi and Maubisse thrust sheets in area T2 (Fig.1.3.1.4). This region has only been surveyed at the reconnaissance level, but Landsat images and topographic maps do suggest that the sheets are intact. There is little evidence of the offsets in the anomaly field which are particularly marked in area T1.

The absence of offsets in area T2 could be due to the presence of a higher strength block which forms area R1, immediately to the north (Fig.1.3.1.4). This is comprised of the allochthonous Aileu Formation, and is 40-50km wide north to south with a metamorphic grade increasing from greenschist facies in the south to amphibolite in the north-east. The Bouguer anomaly field has a relatively steady gradient with values increasing from about 0mGal in the south to +160mGal in the north-east, where the highest metamorphic grades are found. However, much of the northern coast has values in the +70 - 80mGal range. The presence of such a large allochthonous block, which is reportedly not much disrupted (Berry and Grady,1981), dominates a large part of East Timor and has resulted in a smoother anomaly gradient in this region. It is not a thrusted sheet, although thrusting has occurred within the block.

The Bouguer anomaly contours parallel the north coast of East Timor in the R1 area except in the west where they turn sharply south towards West Timor. Here anomaly values increase to +125mGal and the gradient steepens considerably towards the Wetar Strait/Savu Sea. These high values and steep gradients typify area WA1 (Fig.1.3.1.4), an area largely comprised of allochthonous Manamas volcanics and Ultra-basic rocks. These units are considered to be part of the volcanic crustal material in the Savu Sea. Examination of aerial photographs shows that the outcrops have clean, fresh lineations, and rise steeply from the coast and surrounding rocks. Dips are nearly all very steep towards the north which suggests thrusting from this direction. Additionally, the Ultra-basics are commonly tectonically overlain by the Manamas volcanics, which may indicate an original close affinity of the two units as volcanic arc upper crustal units. Elsewhere within West Timor the Ultra basics occur associated with other allochthonous units especially around the region of Gunung (mountain) Mutis (Fig.1.3.1.4). It may be possible that these other allochthonous units were in some regions caught up in a complicated thrust environment associated with oceanic units at the time of, or shortly after, the collision of the Australian continental edge with the subduction zone. The implication of this hypothesis is that the nature of the individual thrust sheets is probably related to the original morphology at the contact zone in any one area. However, the Manamas Volcanics and Ultrabasics near Atupupu and Wini (Fig.1.3.1.4) were probably emplaced after the Lolotoi and associated thrust sheets. Work is presently being carried out to determine more precisely the age of formation and emplacement of these later thrusted volcanic sheets (R.Harris, pers.com.,1988).

1.3.2 THE SAVU SEA AND WETAR STRAIT

North of Timor lie, the Savu Sea, in the west, and the Wetar Strait, in the east. Gravity data for this region come from the the Rama12(1980) and Charles Darwin(1988) cruises (Fig.1.3.2.1).

In the Savu Sea the Charles Darwin sailed close to the West Timor coast which has allowed the anomaly field to be mapped 20-30km off-shore. Off the western end of Timor, Bouguer anomaly values range from +30 to +100mGal in a shallow water region. Australian continental material is probably sited here, a continuation of material seen on-shore in West Timor. Off Wini(Fig.1.3.2.2) values of +150mGal are finally reached, probably marking the junction between Australian continental and volcanic arc rock. Further off-shore in this region values rise to +200mGal. Average values across the Savu Sea toward the volcanic island of Alor probably reach +170mGal. The east-west Bouguer anomaly contour trend in the southern Savu Sea is at variance with the ENE-WSW coastal trend in West Timor. The implication of this is that the Australian Continental Margin extends some 30km off-shore to the north-west of West Timor where anomaly values of +80 to +110mGal and low Bouguer anomaly gradients are measured. If the +110mGal contour is taken to mark the boundary between the Australian margin and volcanic arc rocks then it can be seen that this junction comes on-shore in the eastern half of West Timor in a region of outcrop of Manamas Volcanics and Ultrabasic Formations, i.e. of late-thrusted oceanic/volcanic arc rocks.

Before crossing the former political boundary between East and West Timor the anomaly contours off-shore turn sharply to the north, paralleling the coast. On-shore to the east lies the Aileu Formation which may extend off-shore to the west and north of East Timor. This off-shore extension of Australian allochthonous material creates a strong density contrast against the denser volcanic arc rocks. Steep Bouguer anomaly gradients result, and anomaly contours follow the locus of the site of density contrast.

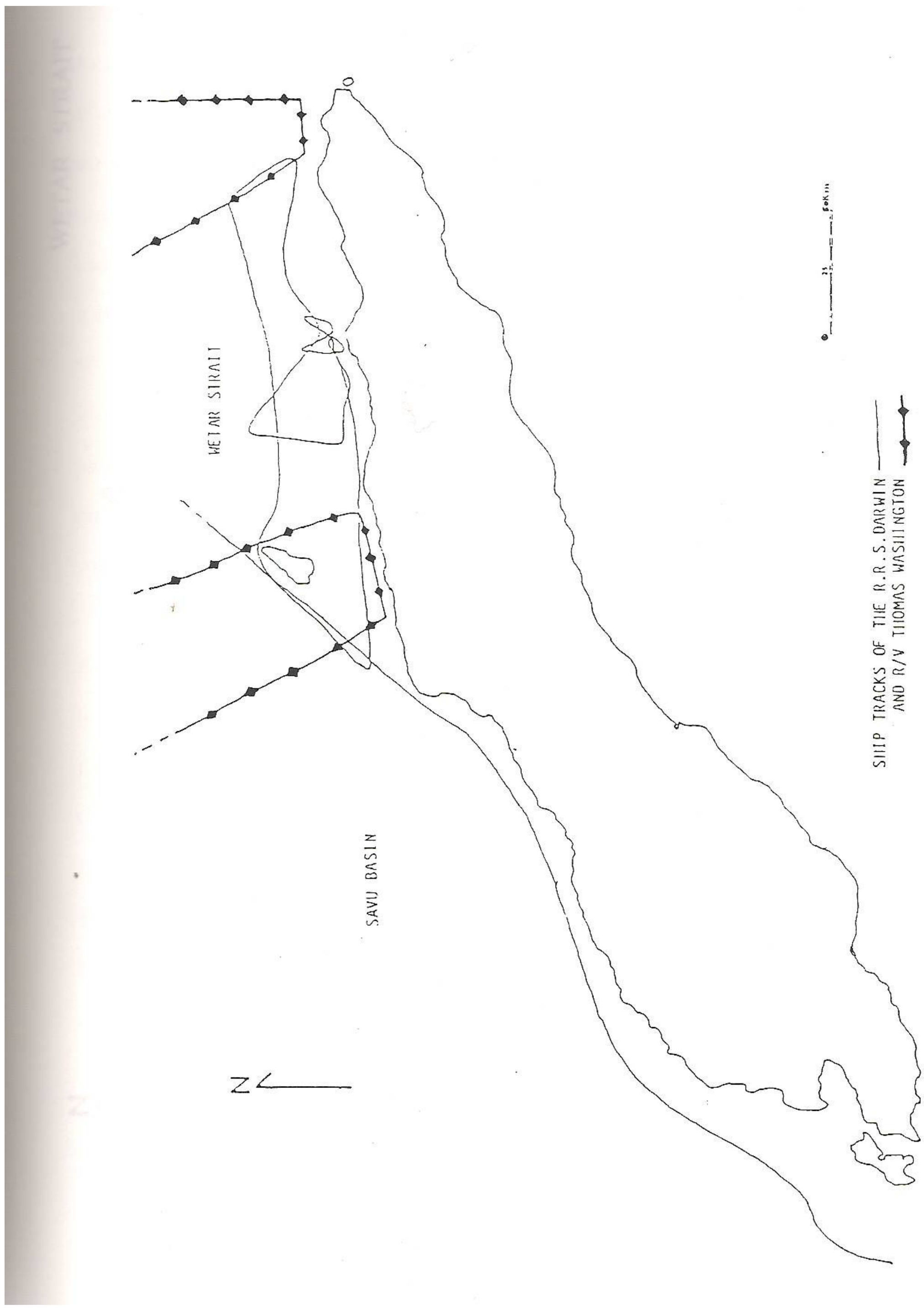


FIGURE 1.3.2.1 Ship track chart

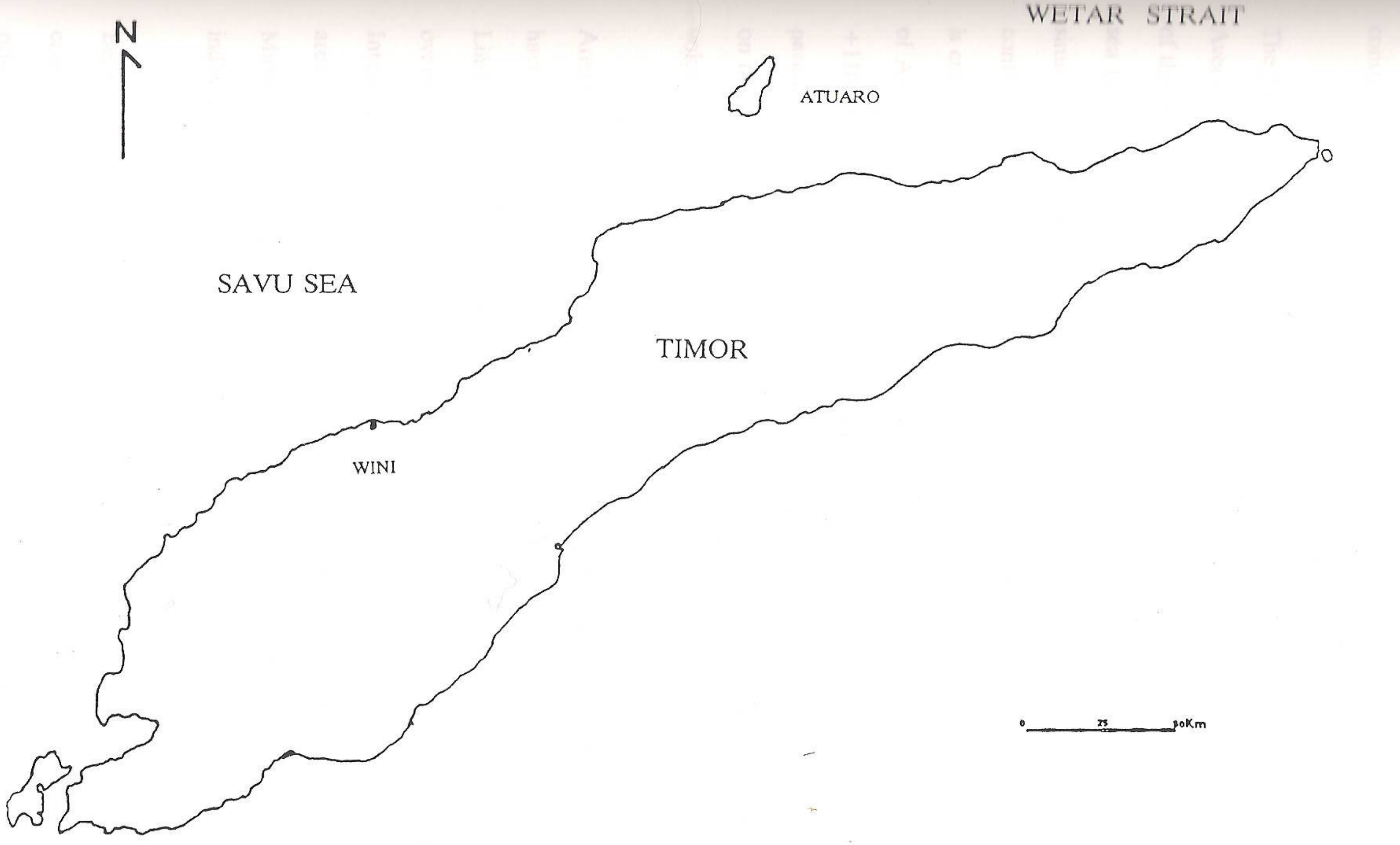


FIGURE 1.3.2.2 Location map

North-east of this region, the extinct volcanic island of Atauro (Fig.1.3.2.2) can be considered to separate the Savu Sea from the Wetar Strait.

The Wetar Strait region has a dominantly WSW-ENE trending Bouguer anomaly field. Average values of between +170 and +180mGal are found in the deepest (3500m) parts of the strait (Figs.1.3.2.3 & 4). Here the Bouguer anomaly pattern and topography of the sea floor are not markedly disturbed. Closer to the north coast of East Timor a strong sinuosity is evident in the anomaly field which is thought to be the result of the continuation off-shore of the NNE-SSW left-lateral offsets found on-shore. This sinuosity is created by the junction between the Wetar Strait volcanic rock and the northward offset of Australian margin blocks relative to each other. Bouguer anomaly values of +50 to +110mGal off-shore East Timor indicate the presence of Australian allochthonous and para-autochthonous units. Conversely, the high values (circa +150mGal) at three areas on the north coast (Map 1, rear pocket and Fig.1.3.2.5) possibly indicate the presence of volcanic rocks on-shore.

Area S1 (Fig.1.3.2.5) west of Manatutu, is a region in which amphibolites and peridotites have been found. Areas S2 and S3, at +110mGal, are the location of the Baucau Limestone Formation, a low density, autochthonous, reefal limestone. The Baucau must overlie dense material which gives rise to the high gravity values and steep gradients. Interestingly, the Charles Darwin dredged samples from a number of sites off-shore from area S2 (Fig.1.3.2.5) which have been likened by R.Harris (pers.comm.1988) to the Manamas Volcanics of West Timor. Anomaly values at the dredge site reach +250mGal, indicative of volcanic material.

Between the dredge site and Atauro island the anomaly contours generally parallel the coast of East Timor, reaching +200mGal some 10 to 15km off-shore. Here a bathymetric ridge borders the coast at a depth of 1500m, before the sea-floor drops sharply to 3500m and anomaly values decrease to +170 to +180mGal. It should be noted that this bathymetric ridge is determined by only one ship track and is consequently not well constrained.

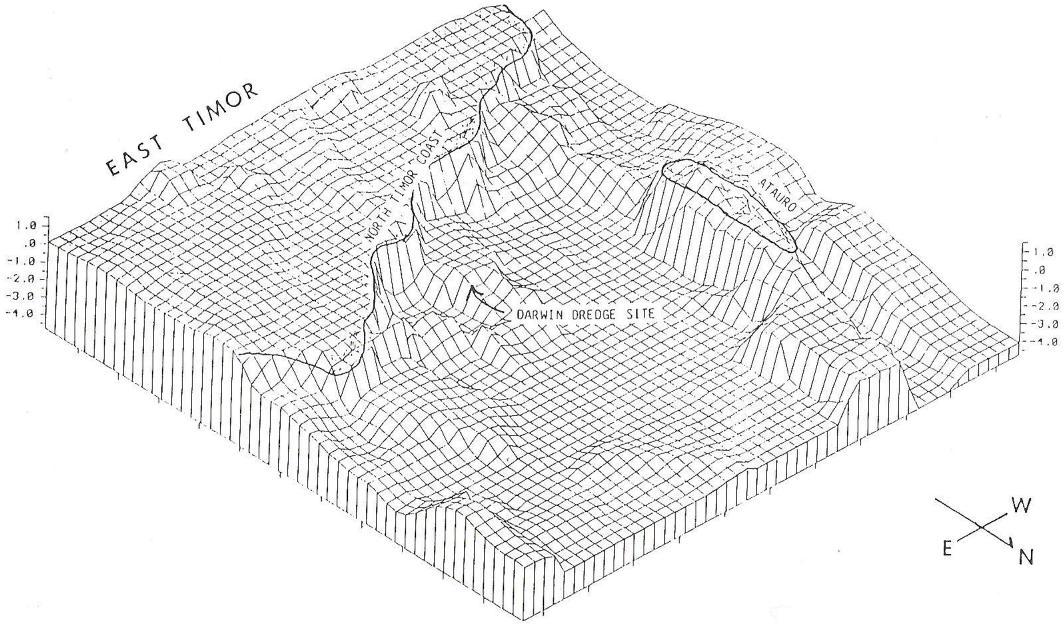


FIGURE 1.3.2.3 Isometric diagram of topography - view from NE.

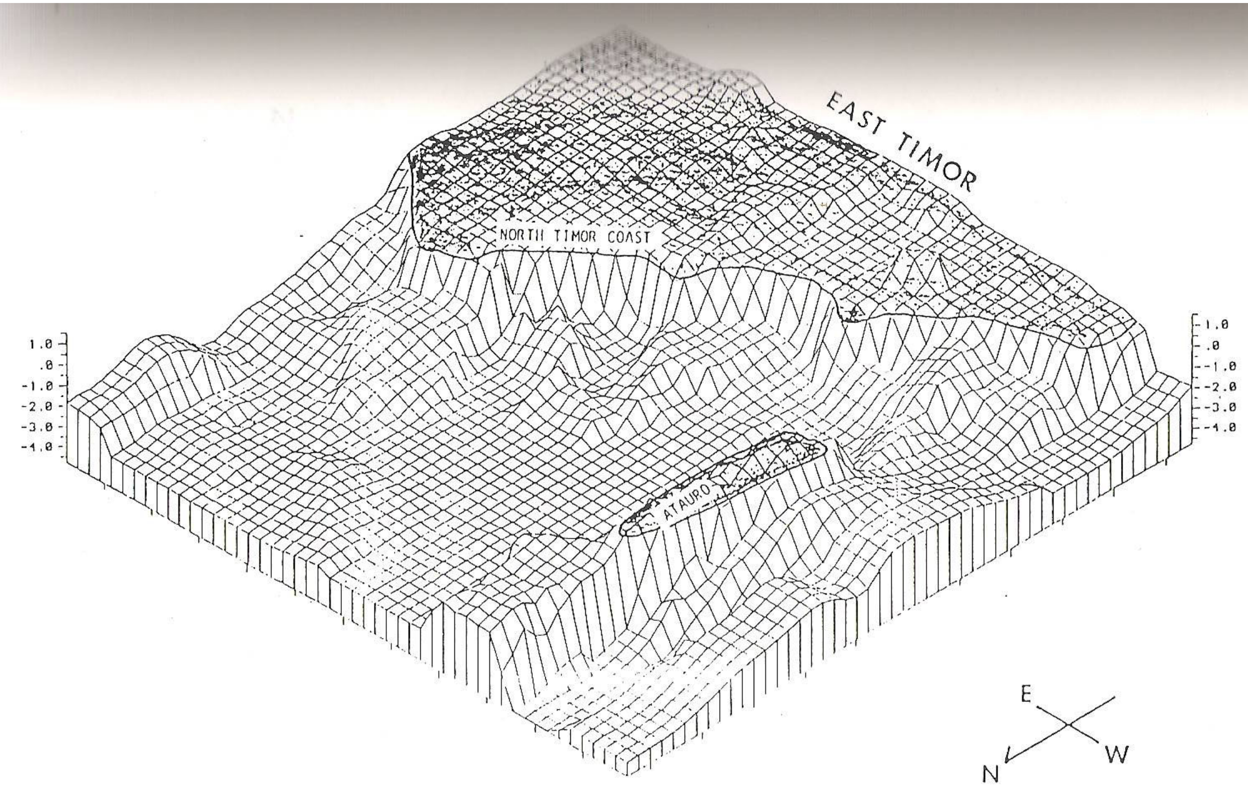


FIGURE 1.3.2.4 Isometric diagram of topography - view from NW.

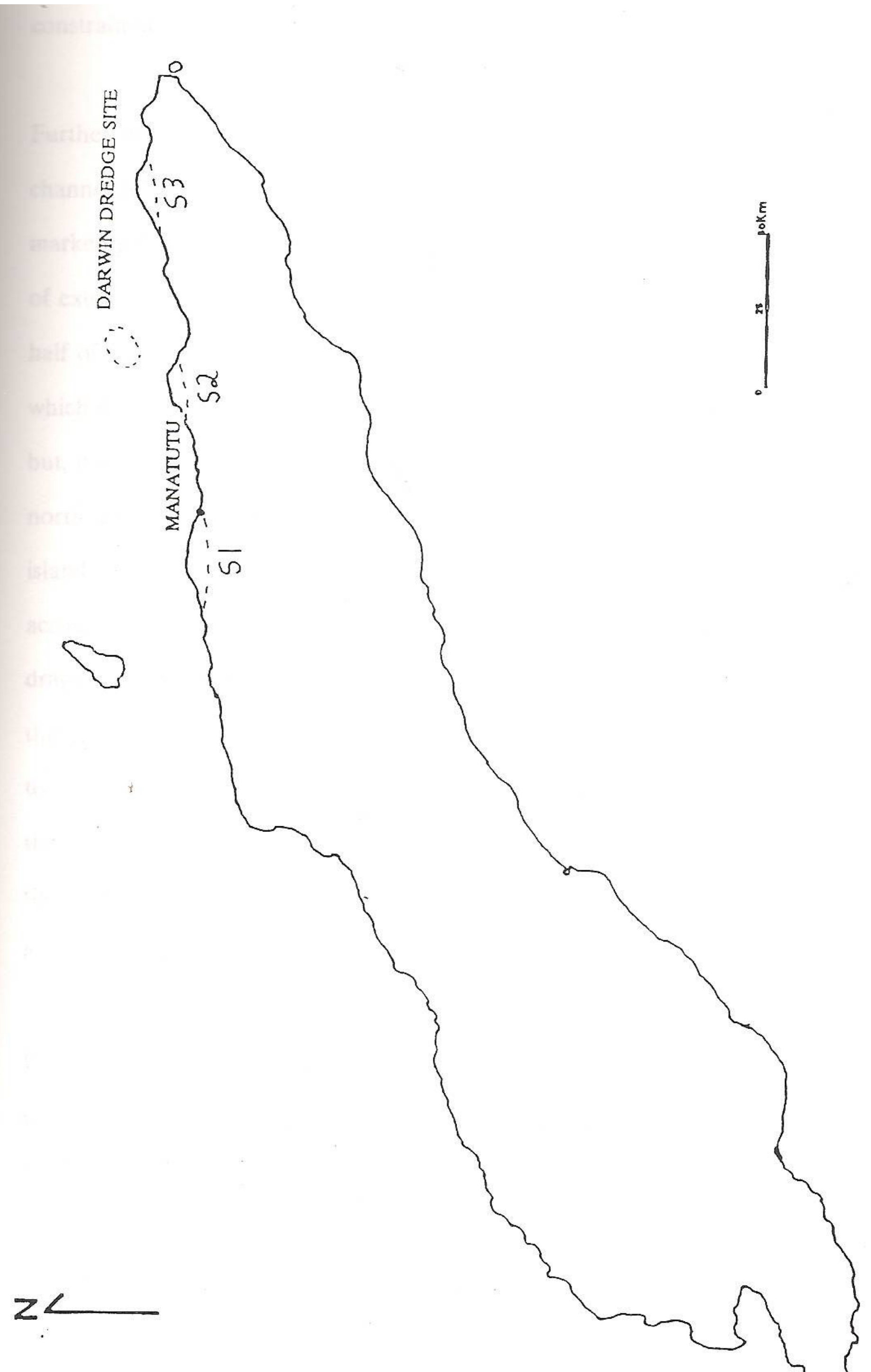


FIGURE 1.3.2.5 Areas with particularly high Bouguer anomaly values on the north coast of East Timor

Further off-shore between the dredge site and Atauro the Charles Darwin shot a single-channel seismic line, south to north across the strait. The northerly dipping reflectors are markedly deformed on the southern half of the line (Fig.1.3.2.6), where there is evidence of extensive normal faulting and soft-sediment slumping and deformation. The northern half of the line shows a virtually flat sea-floor at about 3300m and 1 to 2km of sediments which dip gently to the north. These sediments are little deformed in the upper sections, but, normal faulting is seen at depth with down-throws to the north. Conversely, further north a large normal fault, down-throwing to the south, is clearly imaged. The volcanic island of Wetar, on the up-thrown side, is rising at 3mm/yr. The form of the reflectors across this northern fault indicate considerable drag, although this may be due to the draping of sediments across an active fault. The image is particularly poor at depth near the fault but it would appear that the deeper sediments have been more affected by tectonic activity than those at shallow depths. This may be due to greater fault activity in the past or to the greater influx of recent sediment masking fault activity. Indeed, as both the north of Timor and Wetar are rising at similar rates, the amount of material eroded and transported into the Wetar Strait may have increased with time.

It is notoriously difficult to determine on a seismic image whether a fault is entirely dip-slip or has a strike-slip component. This is particularly true for this image, and it is possible there is strike-slip movement across the fault south of Wetar.

In summary, noteworthy aspects of the seismic image are the lack of compressional tectonics, the northerly dip of reflectors and the sedimentary half-graben adjacent to the fault south of Wetar. These features will be discussed later, together with analysis of the virtually flat Bouguer anomaly field across the strait.

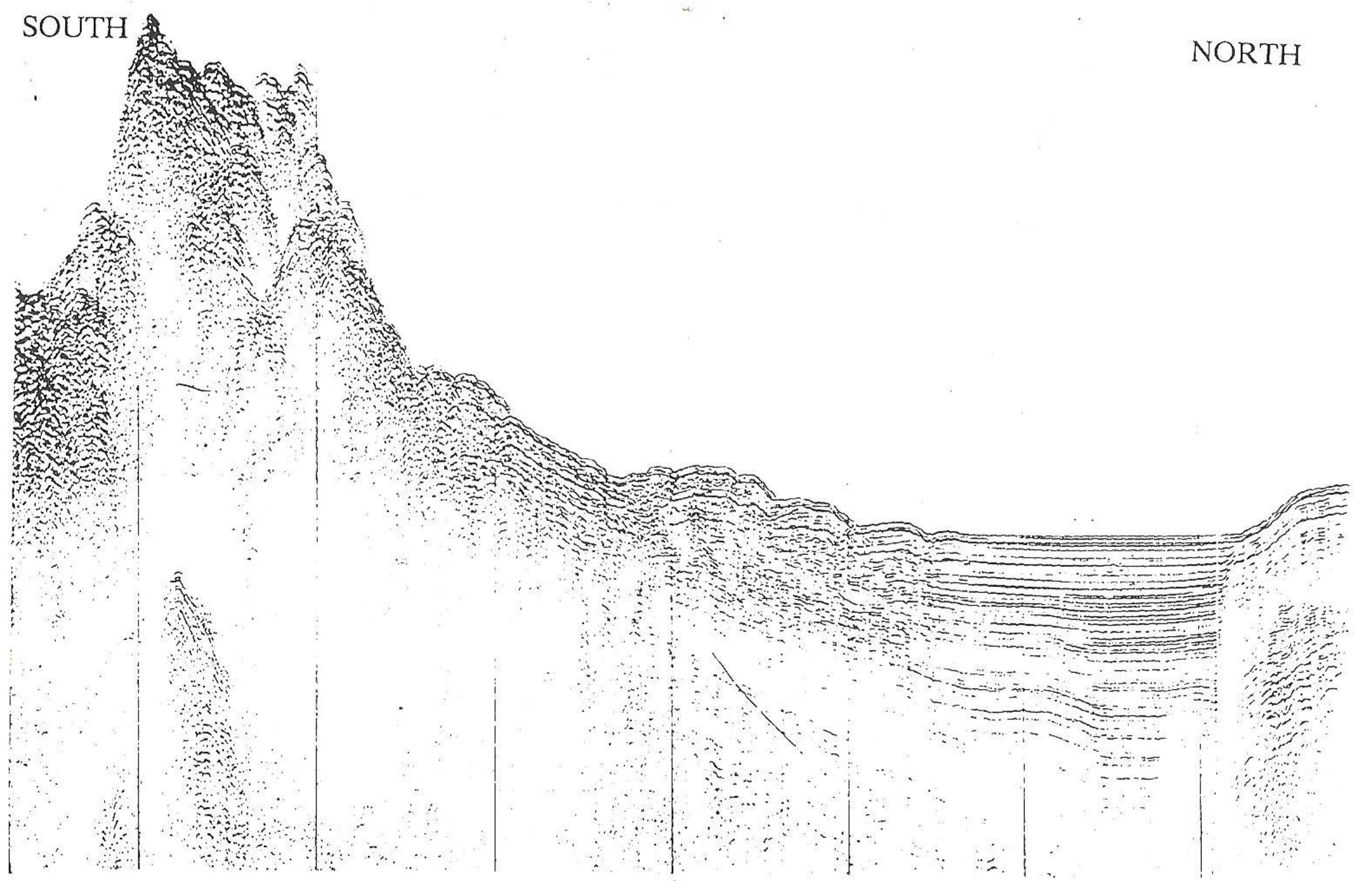


FIGURE 1.3.2.6 R.R.S Charles Darwin seismic image of Wetar Strait

The area surrounding Atauro is in marked contrast to the strait. The isometric bathymetric diagrams (Figs.1.3.2.3 &4) show that Atauro rises steeply from the flat strait to form a ridge orientated NNE-SSW between Timor and Wetar. To the west, and paralleling the Atauro ridge, is a deep (4700m), steep sided and narrow trough. It is this volcanic ridge and trough that separates the Savu Sea from the Wetar Strait and marks a major dislocation between large crustal blocks in the Timor region. The Bouguer anomaly values follow the topographic features, decreasing from +170mGal at the western end of the Wetar Strait to +110mGal on Atauro. West of Atauro the anomaly contours dog-leg across the 4700m deep trough. North of the island values reach +250mGal and may continue to increase northward.

South and west of Atauro the anomaly contours follow various features that can be identified on the GLORIA Side-scan Sonar images obtained by the Charles Darwin in 1988 (Fig.1.3.2.7)

A number of NNE-SSW orientated faults can be seen passing under and to the side of Atauro, thereby creating the Atauro ridge and associated trough. The Ombai Strait Fault roughly parallels the coast of Timor before continuing northward toward Atauro. It is across this fault that the steepest anomaly gradients in the Timor region are found, suggesting that the fault separates the Australian Continental Margin from volcanic material. However, the gradient is increased by the steep topographic slope created by fault activity. Almost certainly, all of these NNE-SSW faults are strike-slip in nature, but there has also been considerable associated dip-slip to form the Atauro ridge and trough complex.

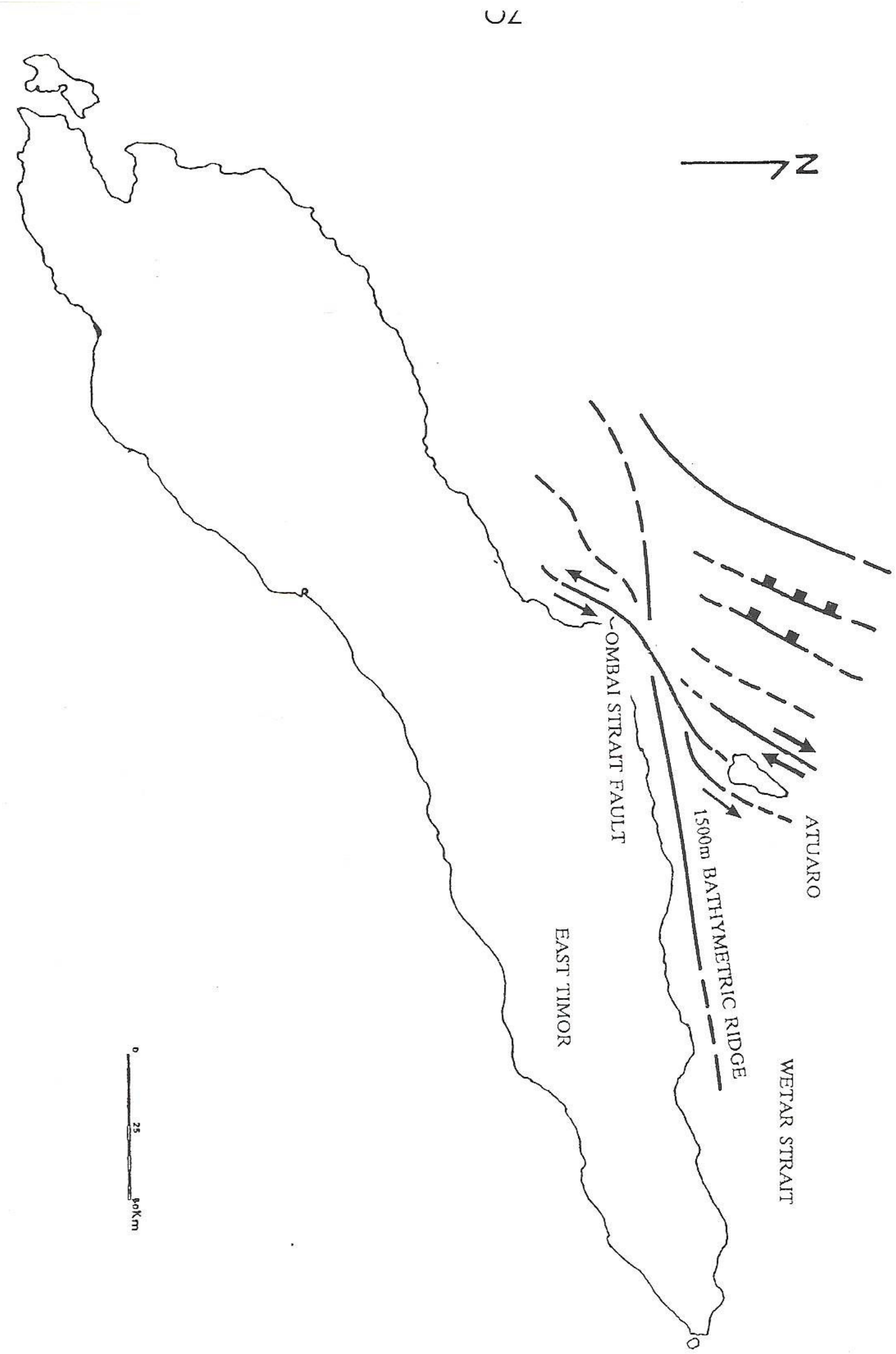


FIGURE 1.3.2.7 Lineament drawing of GLORIA side-scan sonar

The Atauro ridge, although orientated NNE-SSW off the north coast of East Timor, does not come ashore. Instead a region of deeper water separates the ridge from Timor. A west-east trending fault, located at the southern margin of this deeper area, can be followed on the

GLORIA imagery westward into the Savu Sea. This fault marks a southern boundary to the Atauro ridge and trough terrain and causes both the Ombai Strait Fault and the Bouguer anomaly contours to be displaced in a dextral sense. Interestingly, this east-west fault merges further to the east with the 1500m topographic ridge off-shore north Timor which was discussed above. This east-west fault is the southern boundary of a pull-apart basin created by the action of the large, NNE-SSW, strike-slip faults that separate the Savu Sea and the Wetar Strait crustal blocks.

1.3.3 THE UPPER CRUST IN THE TIMOR AREA

The marine data discussed in this section is taken from the Rama12 cruise of the Scripps Institute of Oceanography in 1980 and the Charles Darwin cruise by the National Environmental Research Council(UK) in 1988. Also examined were various geophysical compilation maps of the region and in particular the maps of Bowin et al (1980). The data studied included GLORIA Side-Scan Sonar, Bouguer and free-air anomalies, magnetics, bathymetry and single channel seismic profiles. The aim of the study was to produce a composite map from all of the above sources to show the position of the various crustal block types within the region.

Figure 1.3.3.1 of line drawings of Rama12 single channel, seismic profiles covers the areas around Wetar. All lines show predominantly extensional features from the south near Timor to the north in the South Banda Sea.

Line 7 most clearly shows extension with normal faulted blocks rotating in a southerly direction towards Wetar. Some 20km north of Wetar is a region in which the faults dip more steeply with throws to the north and south. Adjacent to this region are large, fault-bounded, rotated blocks with opposing throws creating a cusp structure. The whole area resembles a classic 'flower structure' and may be the result of a large strike-slip system.

However, this is the area in which the Wetar Thrust (Silver et al, 1983) reportedly outcrops. This thrust is thought to be due to the stress imposed by the continuing northward advance of the Australian Plate causing the initiation of subduction of the South Banda Sea southwards beneath Wetar. All of the lines examined, including line 5 on which Silver et al most clearly see the Wetar Thrust and associated accretionary zone, show extensional features. However, the 'flower structure' described above could accommodate the less than 10km of convergence by thrusting estimated by McCaffrey and Nabelek(1986).

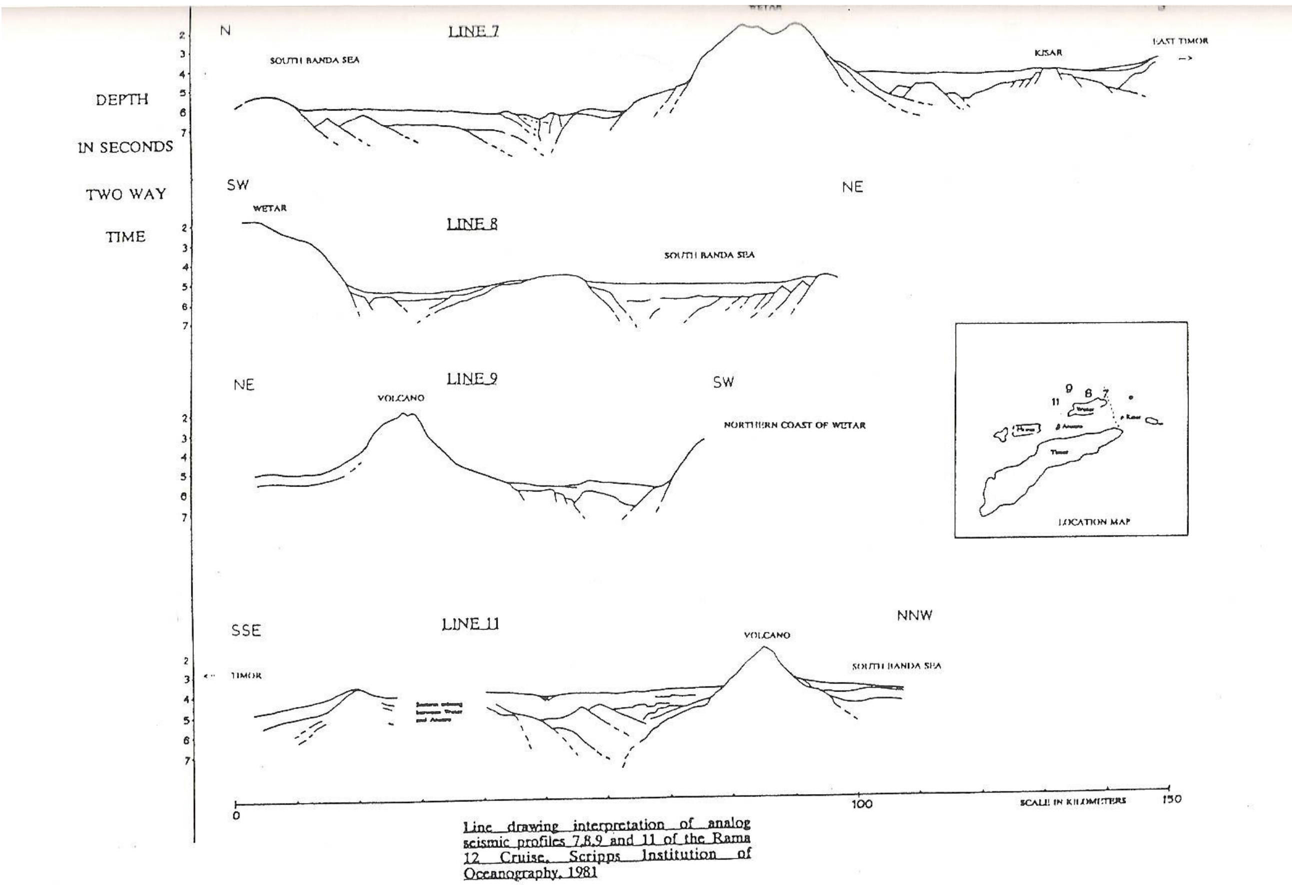


FIGURE 1.3.3.1 Interpretations of Rama 12 seismic profiles

All of the lines show the Wetar volcanic edifice as flanked to the north and south by large, steep, normal faults resulting from the 3mm/yr uplift rate of the island since the collision. The southern end of line 7 passes to the west of Kisar and shows normally faulted rotated blocks with a central horst structure forming Kisar itself. Van Bemmelen(1949) reports that Kisar is formed by a central core of mica-schists, biotite gneiss and quartzite surrounded by fringing coral reef, and is part of the Australian Continental margin.

Rama12 lines 3 and 4 (not shown on Fig.1.3.3.1) pass close to the islands of Leti, Moa and Lakor to the east of Timor, which consist of schist, phyllite, Permian crinoidal limestone and a variety of Palaeozoic sediments, and clearly have Australian affinities.

The geophysical data in this region have been combined to form a lithotectonic map (Fig.1.3.3.2) which will now be discussed.

The 'Oceanic Province' has a depth of 4000 - 4500m, Bouguer anomaly values greater than +275mGal and a magnetic anomaly signature showing high amplitude and short wavelength. All these features are indicative of oceanic crust.

The 'Volcanic Province' has depths in the range 2000 - 3500m with a rugged sea-floor topography, Bouguer anomaly values of +175 - 275mGal and magnetic anomalies similar to those in the 'Oceanic province'. The 'Volcanic Province' encloses all the volcanic islands within the region and is bordered to the south by the 'Australian Continental Province'. The 'Volcanic Province' is therefore a region of past and present volcanic activity and shows considerable lateral variation in width north to south.

The boundary between the 'Oceanic' and 'Volcanic' provinces is relatively sharp to the east of Wetar with steep topographic scarps and a rapid change in the roughness of the sea-floor from smooth over the South Banda Sea to rugged in the volcanic area. The Bouguer anomalies also decrease sharply across the boundary, partly because of the rapidly decreasing water depth. It is interesting to note that the east-west boundary between the 'Oceanic' and 'Volcanic' provinces is some 50km north of the presently active volcanic islands of Damar, Teung and Nila (Fig.1.3.3.2) but the gap decreases to 10km north of the inactive islands of Wetar, Romang and Maopora. This east-west lateral variation is matched by a marked decrease in the width of the 'Volcanic Province'. The junction between these laterally distinct regions is formed by a sharply defined fault mid-way between Damar and Romang (Fig.1.3.3.2). The junction between the 'Oceanic' and 'Volcanic' areas 20km east of Moapora is the site of a large submarine volcano which comes within 600m of the surface and is probably the result of crustal weakness at this fault-controlled junction. The southern continuation of this major dislocation across the volcanic area cannot be precisely located due to a lack of data.

The boundary of the 'Volcanic' and 'Australian Continental' (AC) provinces between Kisar and the Leti Group is poorly constrained except by the evidence of marked bathymetric negative gradients away from the islands on regional bathymetric maps. The ship profiles that do approach the islands show similar features. Here the Bouguer anomaly profiles are typical of those in the north of Timor with steep positive northerly gradients and high values which flatten out at +175 - 200mGal over the Volcanic Province. The bathymetry north of Kisar and Leti shows a rapid drop down to 2000 - 2500m, which is in marked contrast to the smooth sea-floor at 3300m in the Wetar Strait. The sea-floor between Kisar/Leti and the extinct volcanic chain to the north shows rapid changes in depth and is probably much disturbed by volcanic and tectonic processes.

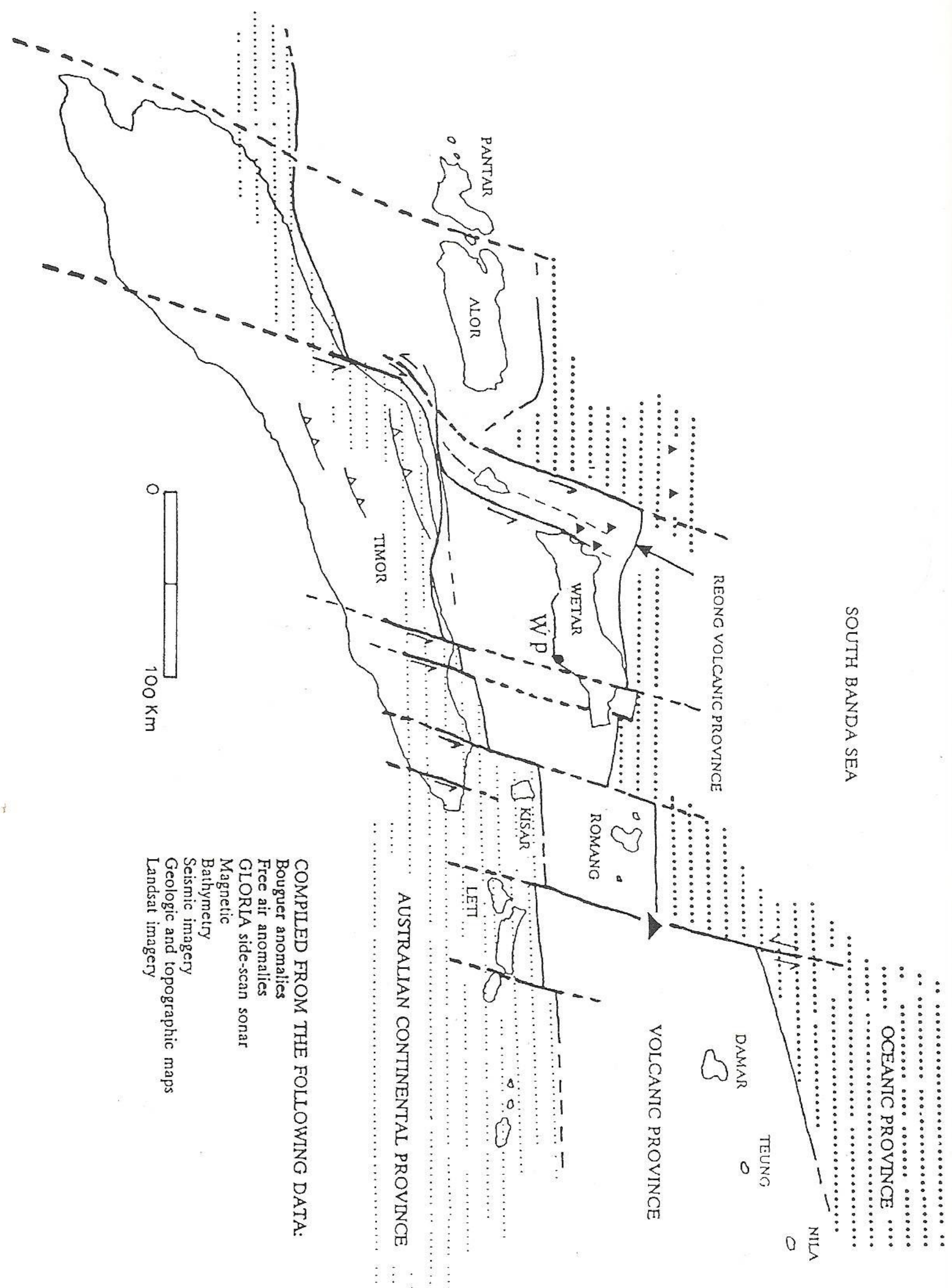


FIGURE 1.3.3.2 Lithotectonic map of the Timor region

A 2500m trough extends from the Wetar Straits eastward south of Kisar and the Leti Group. This trough is considered to be the site of a wrench system that has allowed the eastward translation of Kisar and the Leti Group from the north coast of Timor during the initial stages of collision of the Australian margin with the volcanic arc.

One of the most prominent Bouguer anomaly offsets in East Timor is that which lies to the south of the Charles Darwin dredge site (Fig.1.3.2.5). As already mentioned in section 1.3.2 the Darwin dredge samples that are similar to the Manamas Volcanics and are therefore are probably part of the 'Volcanic Province'. North-north-east of this site the Charles Darwin sailed along the southern margin of Wetar where water depths are remarkably constant except for a region directly south of a promontory (point WP on Fig.1.3.3.2) where depths decrease sharply. The GLORIA Side-Scan Sonar image shows an elongated ridge stretching south-westwards towards the dredge site. The promontory WP is matched by a northern counterpart and a NNE-SSW line joining the two marks a decrease in the north-south width of Wetar to the east. On the lithotectonic map (Fig.1.3.3.2) this line is interpreted as a fault trace which can be linked southwards to the bathymetric ridge off promontory WP and continued across the Wetar Straits to the dredge site and associated inflection in the Bouguer anomaly field. The fault has been continued on-shore in East Timor to follow the NNE-SSW offset in the Bouguer anomaly field across Timor.

The next large offset in the geophysical data occurs to the west of Wetar and is a continuation of the zone of crustal dislocation in the Atauro region discussed in section 1.3.2. The GLORIA images to the north and west of Wetar show a number of submarine volcanoes which appear to be young, having lava flows evident on the sea-floor. This region has been named the Reung Volcanic Province. The boundary faults to this province are shown on Fig. 1.3.3.2 as continuations of those either side of Atauro and are defined by the marine geophysical data. Atauro is now extinct, the oldest rocks being dated at 3my old, a date linked to the collision of the Australian continental margin with the volcanic arc. As has already been mentioned, the volcanism on Atauro is thought to be due to extension within a fault-controlled graben. The apparently young appearance of the volcanoes in Reung Volcanic Province suggests that extension has continued further to the north with time. The oldest reported rocks from Wetar are 3my old but J.S.Milsom (pers.com.1988) considers that volcanic landforms on the west coast of Wetar indicate much more recent activity. Additionally, the Rama12 data shows the presence of volcanoes NW of the Reung Volcanic province. It seems probable that the zone of extension, graben formation and volcanism is younger and more diffusely spread to the north and west of Wetar than previously supposed. Undoubtedly, the relative movement of crustal blocks in this region has produced a complex tectonic environment.

To the west of Wetar are the presently active volcanic islands of Alor, Pantar and Flores which are separated to the south from West Timor by the Savu Sea. These geographical units form one large crustal block which is separated by the Atauro/Reung Volcanic Province graben system from a similar crustal block to the east consisting of Wetar and Romang, the Wetar Straits and East Timor. On Fig.1.3.3.2 the trends of major structural features show that the eastern crustal block has moved northwards relative to the western by approximately 40km.

CHAPTER 1.4

CROSS-SECTIONAL MODELLING OF TIMOR.

1.4.1 THE MODEL LINE AND OBSERVED DATA.

The Bouguer anomaly profile chosen for the modelling (Fig.1.4.1.1) extends northwards from the Australian Continental Shelf across the Timor Trough into East Timor, continues northwards across the Wetar Strait and Wetar and is terminated in the South Banda Sea.

This line was chosen because it crosses areas which are comparatively well known, both geologically and geophysically; in East Timor it coincides with the profiles by Milsom and Richardson(1976), Chamalaun (1977) and Milsom and Audley-Charles (1986).

The observed anomaly data over the South Banda Sea has been taken from Bowin et al (1980) and the Rama12 and Charles Darwin cruises. From the south coast of Wetar to the south coast of Timor the profile is based on data collected by the Rama12 and Charles Darwin cruises and on the land data compiled during this study. Data south of Timor are taken from the compilation maps of Bowin et al, (1980) and from maps produced by the Australian Bureau of Mineral Resources on the basis of work done between 1970-6 (Watt,1976).

Values over the Australian Continental Shelf are typically +55 to +60mGal, decreasing steadily northwards towards the Timor Trough where values reach 0.0mGal. The gradient continues to be negative towards the south Timor coast except for a few minor fluctuations which, based on the wavelength, appear to be due to shallow density variations within the imbricate wedge. The lowest values, of about -45 to -50mGal, occur adjacent to the south coast of Timor, where the gradient reverses, becoming positive northwards. In the southern half of Timor the gradient is moderately steep at around 1mGal/km. This reflects the dual

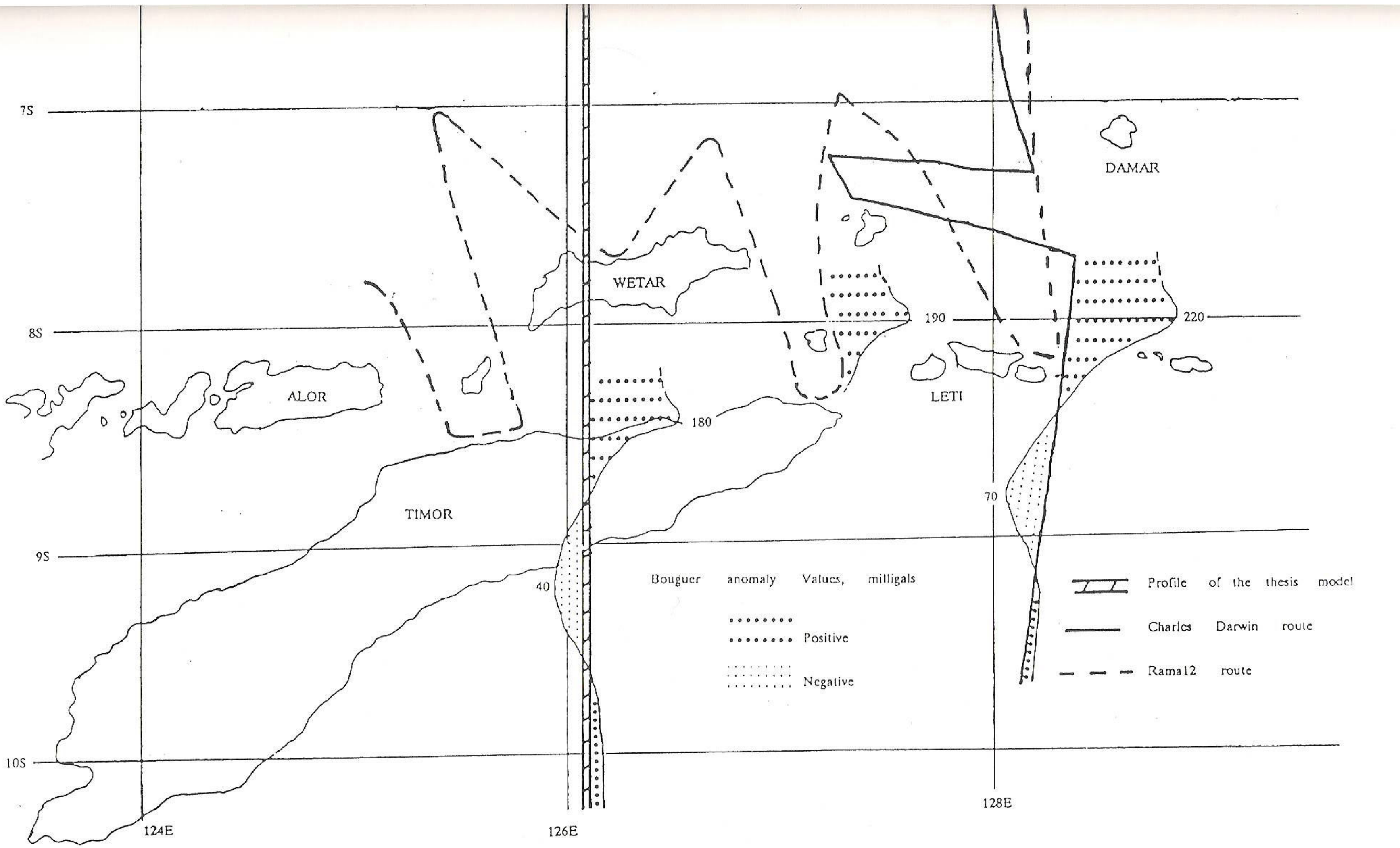


FIGURE 1.4.1.1 Model line plus Darwin and Rama12 lines

influence of the high density volcanic material in the Wetar Strait and the medium density, but closer, units of the allochthon, on the low density units of the para-autochthon and autochthon in the south. From the middle of the island northwards the gradient begins to steepen sharply reflecting the presence of allochthonous units. Localised, steep, positive, inflections in the anomaly profile are due to allochthonous nappes overlying the para-autochthon. Nearer the north coast the anomaly gradient continues to steepen to 7mGal/km due to the influence of the dense material in the Wetar Strait.

Directly off-shore, anomaly values reach +200mGal before decreasing sharply to +180mGal. The line chosen across the strait avoids the complex structures adjacent to Atauro and the consequently locally anomalous observed values. The observed values across the strait are remarkably consistent at approximately +175 to +180mGal from 10-15km off-shore north Timor as far as the southern margin of Wetar. No data are available for the island of Wetar and as a consequence none are displayed on the model. However, observed data from marine cruises crossing the Inner Banda Arc and land data from volcanic islands around the world in similar settings have been examined and used to model the crustal structure of Wetar. North of Wetar the observed values become steeply positive, increasing from +170 to +300mGal some 55km north of Wetar. This gradient and associated high values are due to the oceanic character of the crust of the South Banda Sea.

The model profile is typical of nearly all profiles across the Banda Arcs. Figure 1.4.1.1 shows the model profile and those for the Rama12 and Charles Darwin cruises to the east of Timor. It can be seen that the profiles are broadly similar with nearly identical gradients and values across the whole of the Banda Arcs. There are local differences between profiles, and values do vary depending upon water depth and local thicknesses of crustal units. However, it is clear that the chosen model line and resulting model could, with minor modification, be applied to other north-south anomaly profiles.

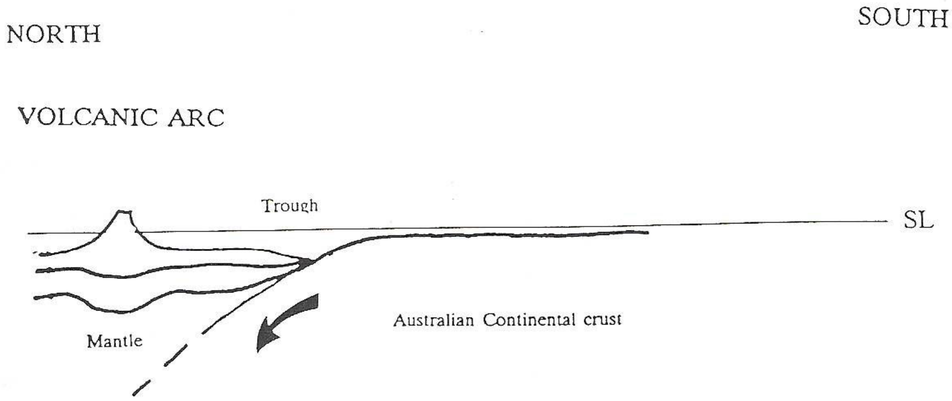
1.4.2 DESCRIPTION OF MODEL ONE (1) (rear pocket).

The South Banda Sea is considered by nearly all workers to be oceanic and has been modelled as such with polygons 3 and 4 representing oceanic layers 2 and 3 at densities of 2.7 and 2.89g/cc respectively. The depths to layer boundaries have been based on refraction experiments elsewhere in the region (Bowin et al,1980) and on standard oceanic crustal thicknesses.

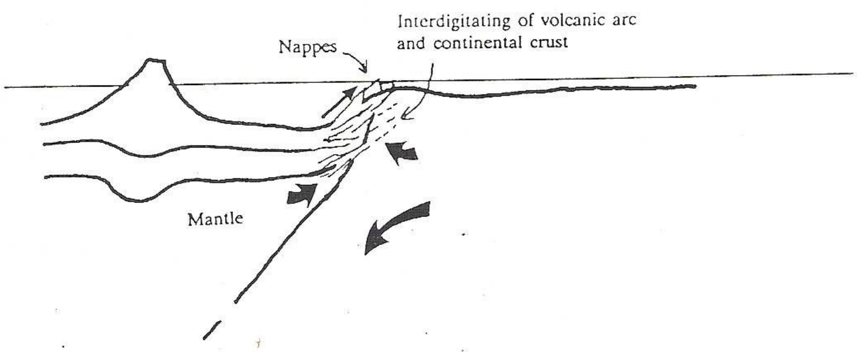
Immediately off the north coast of Wetar, the Bouguer anomalies increase steeply to the north while single channel seismic images show a few low density sedimentary basins close to Wetar. These basins are typical of other island arcs around the world and in the case of Wetar are probably due to the action of steep normal faults created by the uplift of Wetar. This rapid uplift and consequent erosion is supplying the detritus for the small basins. A similar story can be invoked for the basin to the south of Wetar, although here the tectonic development is more complex. As already explained, the structure of Wetar in the model is a composite of other island arcs around the world. For the ease of modelling, polygons 3 and 4 have been continued from the South Banda Sea southwards to represent the structure of Wetar. The boundaries between the two polygons and the deeper mantle material of polygon 5 are steep away from the island, reflecting the composites from other regions and the anomaly gradients north and south of Wetar.

The observed anomaly profile across the Wetar Strait is almost flat at +175 to +180mGal. The single channel seismic line of the Charles Darwin, described in section 1.3.2, shows 1-2km of low density, recent, sediments close to Wetar which decrease in thickness towards Timor. The sediments show little compressional deformation, except for gravity sliding, and the increasing depth of the basement of the basin through time is indicative of subsidence south of Wetar. This subsidence appears to be confined to the north of the Wetar Strait, with Wetar rising along a dip-slip fault close to the south coast. At the southern end of the Wetar Strait is the high density material of polygon 6. The southern vertical face of this unit is effectively the suture between the volcanic arc and the Australian Continental Margin. This mantle material is responsible for the +200mGal values and sharp gradients adjacent to the north Timor coast. The southwards thinning of recent sediments in the strait and the imaging of the basement dipping northward, away from the upthrust mantle, indicate that the Wetar Strait as a whole has tilted down to the north. However, a simple tilting of this block, assuming constant thickness and density of units across the breadth of the block, would not produce a flat Bouguer anomaly field. Consequently, there must be a balancing of the effect of the low density units in the north by a greater volume of higher density material in the south. This has been achieved by thickening the lower crust (polygon 4) in the southern half of the Wetar Strait.

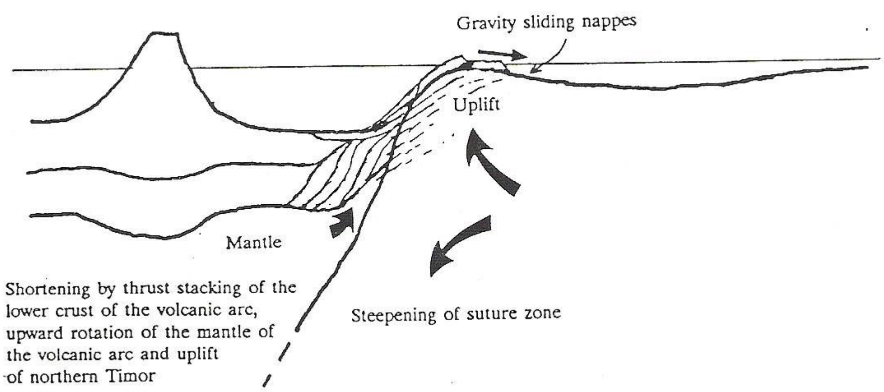
Figure 1.4.1.2 shows the thickening and development of the suture zone. Prior to the collision in the Late Miocene/Early Pliocene the Australian oceanic crust was subducting northwards under volcanic arc material (Fig.1.4.1.2A). During the first stages of collision (Fig.1.4.1.2B) the leading edges of the Australian craton and the arc were interdigitated by thrusting, creating southerly thrusted nappes. This explains the juxtaposition of some of the Australian sedimentary allochthonous units with ultrabasics, meta-basics and serpentinites in West Timor. At deeper levels in the lower crust of the arc, the convergence stress may have been taken up along northward dipping thrust faults (Fig.1.4.1.2C). At the same time the suture zone may have steepened, resulting in the upthrusting of the leading edge of the upper mantle in the arc. Continuation of these processes may produce a stacked sequence of the lower crustal units, bordered to the south by upthrust mantle (Fig.1.4.1.2C). This stacking is modelled in the increased thickness of polygon 4, that, in part, counter-balances the low density sediments in the Wetar Strait, thereby producing a flat calculated Bouguer anomaly field.



A) Immediately prior to the arc-continent collision



B) The first stage of the collision



C) Later development

FIG. 1.4.1.2 EARLY DEVELOPMENT OF THE SUTURE ZONE 84

The configuration of the polygons directly north of Timor are not fully representative of reality, there probably being considerable tectonic mixing of arc rock with the Australian crust. The thrust stacking of the lower crust of the arc may be responsible for 40-50km of shortening, assuming an initial thickness of 5-6km. Of course, the original configuration is unknown and the shortening may be more, or less, than implied.

The upthrust mantle of the arc (polygon 6) causes the highest (+200mGal) Bouguer anomaly values on, or adjacent to, Timor. During modelling it became clear that a unit of this density and form was necessary to produce the required gradient and values. Many other configurations were tried, but, the one presented best fits the known geology. For example, the Charles Darwin dredged samples similar to the Manamas Volcanics at a site that corresponds in position to polygon 6 and has Bouguer anomaly values of +250mGal. The Manamas and Ultra-basic Formations were the latest units to be thrust from the Wetar Strait, and the upthrust mantle of polygon 6 may be the root zone for these units.

Through the volcanic province the Moho for the model is drawn at 35km, below which is mantle material at a density of 3.270g/cc. The approximate surface of the subducting lithosphere is known from the location of earthquake foci. This surface is inclined at 60 degrees, a figure consistent with the work of Cardwell and Isaacs(1981,1978) and Cattaneo and Mercanti(1988). These authors report the possible rupturing of the subducting plate at depths of around 50-100km. However, the exact configuration is unknown due to ambiguity in some of the results, and gravity modelling of materials at these depths with a low density contrast would not contribute to these studies.

In north Timor the Moho is modelled at 35km, descending to 45km some 30km south of the island (polygon 18), before ascending under the Australian Shelf to 30km (polygon 19). The raised mantle under the Australian Shelf, represented by polygon 19 at 3.0g/cc, is consistent with refraction studies conducted by Jacobson et al(1978), which indicated Moho depths between 34 and 26km. Polygon 18 at 3.0g/cc thickens the crust from the Timor Trough, southward to Timor, as far as the middle of the island. This polygon is necessary to model the long wavelength anomaly low directly north of the Timor Trough. Without this unit, the thickness and volume of the para-autochthonous and autochthonous units of polygon 14 have to be unrealistically enlarged.

The combined gravitational effect of polygons 18 and 19 control the long wavelength anomalies from the middle of Timor southward out over the Australian Shelf. North of this area, the northward positive anomaly gradient is modelled by the juxtaposition of the high density material of the arc (polygons 6 and 7) against the continental margin units of polygons 10,11 and 16, together with the effect of the steep Benioff zone.

The allochthonous units on Timor are modelled by polygons 10, 11 and 16. Polygon 10 represents the Aileu Formation and other sedimentary, allochthonous units. Polygon 10 starts off-shore of north Timor at a thickness of 6km, before thinning southwards, where nappes are modelled by varying the thickness of the polygon over the para-autochthonous units of polygons 12 and 13. The thickened northern section is designed to represent part of the root-zone of the thrusted nappes. The form of the polygon over the middle of Timor adequately accounts for the short wavelength positive gradients in the observed profile. Here the nappes are modelled at 1-2km thick and at a density of 2.68g/cc. Some variation in the thickness and density of this polygon could be introduced to account for local density changes due to changes in the metamorphic grade of the Aileu Formation. The density has been chosen after an examination of rock samples, descriptions of outcrops and reference to the work of Chamalaun, et al(1976). Chamalaun quotes a mean density of 2.83g/cc for the Lolotoi Complex, a figure 0.15g/cc higher than that used in this study. If 2.83g/cc is the gross density of the nappes, then the thickness of the nappes is nearer to 1km, rather than 2km.

Part of the root-zone to the nappes is thought to exist north of Timor, at the northern edge of polygons 10, 11 and 16. Within this area, basement rocks of the former passive margin may have collided with the volcanic arc, and have undergone contact and regional metamorphism, together with considerable tectonic disturbance. Tectonic mixing may have occurred at depth between these units and the deeper levels of the arc. The form of the model suture line implies that Australian continental material below 20km, has moved further north than the upper levels. This may be due to the collision stress being accommodated by ductile flow in the mantle of the arc, while the upper levels have undergone brittle failure leading to the stacking of the lower crust of the arc.

The collision may have caused the serpentinisation of some of the basic rocks of the arc, which may have created a semi-ductile medium for the movement of thrust sheets. For example, near Atupupu in West Timor Helmers et al (1987) report the association of peridotite-mylonite high grade rocks with horneblende-diorites and gabbros, bordered by pelitic, amphibolitic and marble mylonites and serpentinite. These authors compare the chemistry of the amphibolite mylonites to the meta-gabbros of the Mutis Complex. They speculate that the Atupupu peridotites and mylonites were formed in an obducted terrain, which possibly implies the former presence on-shore of a large basic and meta-basic unit. However, gravity modelling suggests that this obducting body is still off-shore as polygon 6, and that the various meta-basic complexes, and some nappes, were emplaced following tectonic mixing, and southward thrusting, of slices from the suture zone during the initial stages of collision. The Atupupu rocks may have been thrust ashore by the obducting mantle (Polygon 6), at a later stage in the collision.

Further south on Timor, and in places hidden by allochthonous sheets, are the imbricated and underplated para-autochthonous units of the Australian margin (polygon 12). The density of 2.56g/cc has been chosen after a consideration of rock descriptions by a number of authors. Polygon 12 descends from 1 to 20km, and probably has considerable density variation within it. Densities in the lower portion, especially adjacent to the north coast units, may be appreciably higher than modelled. If the density is increased, then as compensation the thickness of the crust beneath north Timor has to be increased.

The autochthonous molasse and recent deposits of southern Timor, lie upon, or within, the para-autochthon. These rocks are in part represented by polygon 14 at density of 2.5g/cc. This density is obviously too high for molasse deposits alone. However, most of the polygon comprises para-autochthonous slope and shelf units of the Australian margin, similar to those of the Kolbano Complex in West Timor. These Mesozoic and Tertiary sediments are modelled in polygon 14 southward beneath the Timor Trough, and onto the Australian Shelf. The thickness of this unit, and the underlying sedimentary basement modelled by polygon 15, is largely based upon the refraction studies of Jacobson et al(1978). The Timor Trough may now be a foreland basin created by the southward movement of para-autochthonous units within polygon 14. The decollement separating these units from the sedimentary basement is modelled by the near horizontal boundary between polygons 14 and 15, which may extend further north as the boundary between polygons 13 and 17. The inclination of the decollement has been constrained by the theoretical studies of Davis et al(1983) (see section 2.2.3.1 on Tanimbar modelling for a description).

Shortening of the collision zone, due to the continuing convergence of the Australian plate, may be accomplished by underplating and overthrusting within the various units of the Australian margin, which is reflected in the northward thickening of polygon 15.

The Australian lower crust is modelled by polygon 17 at a density of 2.89g/cc, a value derived after consideration of the refraction studies of Jacobson et al (1978) and Bowin et al (1980).

1.4.3 DISCUSSION OF MODEL ONE (1)

The model described above is, for this part of the world, well constrained by geophysical and geological data. However, there are a number of possible model variations which are significant when considering the tectonic development of the region.

Firstly, the long wavelength Bouguer anomaly low, centred 55km south of the Timor coast, has been modelled by increasing the thickness of the crust in this region (polygon 18). However, there is obviously an interplay between the densities of units above polygon 18 and the depth to which this polygon can be extended. If the chosen density (2.5g/cc) of the para-autochthonous and autochthonous polygon 14 is too high, then the thickness of the crust should be decreased. However, it is more probable that the chosen density is too low, which, if increased, would require a increase in crustal thickness.

Secondly, and converse to the discussion above, the densities of the para-autochthonous and Australian sedimentary allochthonous units in the north of Timor (polygons 10, 11, 12 and 16) may be too low. They are almost certainly not too high. If these densities were increased, the crust under north Timor would have to be thickened, or the volume of polygons 10, 11, 12 and 16 decreased. If all of the compensation was by the extension of polygon 18 northward towards the Timor coast, the increase in crustal thickness would not be more than 3-5km, following density increases of 0.03 to 0.1g/cc in polygons 10, 11, 12 and 16. These hypothesised density increases do have significance for the provenance of polygons 11 and 16, that is, they are no longer clearly of Australian continental affinity, and could be classified as part of the arc. This is particularly true for polygon 16 at a deeper level.

If the origin of this polygon is in the lower crust of the arc, (it would not be dense enough to be mantle) then at the time of collision it must have been carried down to a depth below 35km and has subsequently risen along with the rest of northern Timor. Additionally, this model implies that the allochthonous nappes, and their associated root-zones (polygons 10 and 11, respectively), have been thrust northwards over the depressed leading edge of the arc, and that later in the collision these nappes were thrust southwards. If, however, polygon 16 represents part of the former Australian oceanic plate, then it must be assumed that either subduction stopped 3-4my ago at the time of collision, or, that this remnant was caught up in the collision process, ruptured from the rest of the oceanic plate, and was then overridden by the Australian continental margin, and depressed to its present depth. Seismicity defines a Benioff zone dipping northward from Timor down to 600km, and so the first consideration can be discounted. The second idea is more plausible, and is circumstantially supported by the work of others. For example, Falvey and Mutter(1981), and others, depict the leading edge of a passive margin as a thinned crust underlain by material approaching mantle densities, bordered by oceanic rock. Additionally, McCaffrey et al (1985), using fault plane solutions, suggest that the Australian continental lithosphere in the Timor region, has been subducted to a depth of 50-100km. Therefore it may be possible for deeper, dense material to be subducted, while the upper crustal material is ruptured away and thrust over the trapped Australian oceanic rock.

1.4.4 DESCRIPTION AND DISCUSSION OF MODEL TWO (2)

Model 2 (rear pocket) is based on model 1, and consequently has many similar features and polygons, and so only changes to model 1 will be discussed.

Model 2 attempts to account for the gravitational effect of Australian, intermediate, crustal material being subducted to depths of approximately 90km. This has been accomplished by the extension of polygon 20, at a density of 3.15g/cc, from the Moho under the middle of Timor down to approximately 90km.

Model two is based upon the assumption that continental crust can be subducted. The question is, how much? McKenzie(1969) calculated that very little continental crust could be subducted because of its high positive buoyancy. This has been interpreted by most workers to mean that no continental crust can be consumed at a subduction zone. However, later work by Molnar and Gray(1979) shows that approximately 10km of continental crust could be subducted, if the upper and lower crust could be detached from one another. These authors point out that there is considerable flexibility in the amount of continental crust that can be subducted, related to the size of the parameters used to determine the negative and positive buoyancy forces. This flexibility would allow the subduction of 30km of continental crust. The largest unknown factor in determining the negative buoyancy, is the size of the gravitational body force, of the already subducted oceanic lithosphere, that can be transmitted to the surface. If all of this force were transmitted then hundreds of kilometres of continental crust could be subducted.

The original shape of the colliding continental margin will also determine how much of the continental crust can be subducted. If a thin peninsular, or a small continental fragment, at the leading edge of the margin collided first, then the low positive buoyancy of these fragments would allow them to be subducted entirely.

Having consideration for the above comments, it is apparent that a limited, but unknown, amount of continental crust could be subducted, and that this amount will vary depending upon a number of parameters. One factor that is not known is the effect of the 'push' force from the northward moving Australian lithospheric plate.

In model 2, the low density, subducted, intermediate material (polygon 20), has been partly compensated by increasing the densities of the sedimentary allochthon (polygon 11, 2.8g/cc) and the Australian meta-basement (polygon 16, 3.0g/cc). To maintain the correspondence of the calculated with the observed Bouguer anomaly values over the Wetar Strait, the density (3.1g/cc) and volume of the obducting mantle of the volcanic arc (polygon 6), has been increased, while the densities of the mantle of the volcanic arc, and oceanic plate, (polygons 5 and 7) were increased to 3.3g/cc. This results in a calculated anomaly profile over the Wetar Strait that is no longer flat as required. This was corrected by decreasing the thickness of the consolidated sediments (polygon 2), directly south of Wetar.

The Benioff zone, from 35km to 140 km, has been steepened to 75 degrees, but at greater depths the gradient remains at 60 degrees and is therefore still compatible with the zone mapped from seismicity (Cardwell and Isaacs 1981,1978; Cattaneo and Merlanti 1988).

Some 45-50km south of Timor, the thickness of the Australian crust has been decreased (polygon 18) to compensate for the long wavelength, negative effect of the subducted intermediate crust (polygon 20).

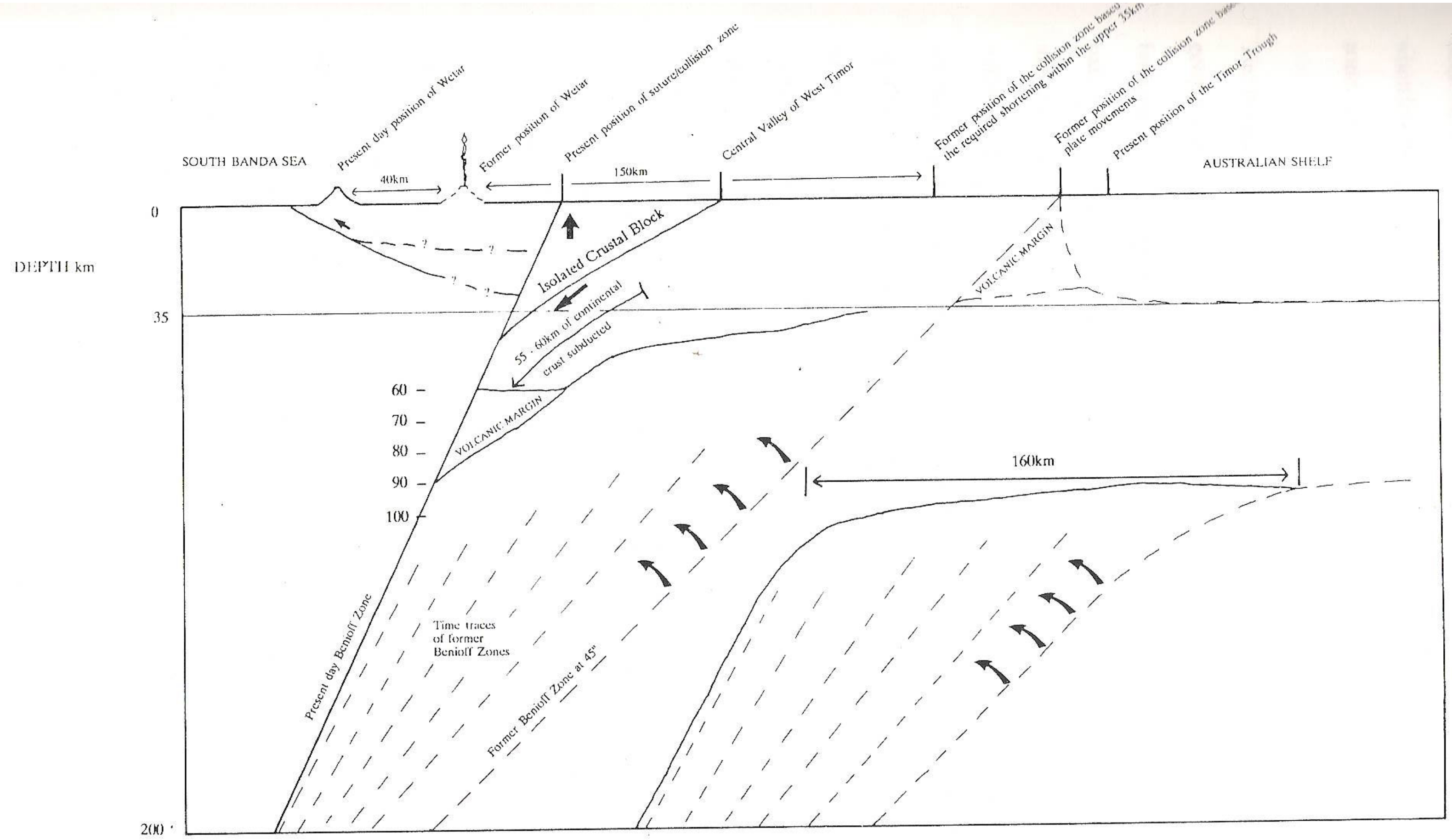
1.4.5 SIGNIFICANCE OF THE DIFFERENCES BETWEEN MODELS ONE AND TWO

For the last 3my, the Australian plate has beeen converging on the South Banda Sea at a rate of 7.5cm/yr (Minster and Jordan 1978). The required shortening of 225km must be adequately explained both in the crust (0-35km) and at deeper levels.

Figure 1.4.5.1 graphically accounts for the required shortening. Some 50km of shortening between the volcanic arc and the suture/collision zone has already been described in the modelling, where the collision has caused the overthrusting and stacking of the lower crust of the arc, accompanied by the upturning of the leading edge of the mantle of the arc. Additionally, Model 2 requires a thickening of the upper mantle, directly north of the suture/collision zone.

The compilation of the marine geophysical data (section 1.3.3), indicates that the major crustal block containing East Timor, the Wetar Strait and Wetar Island, has been displaced northward by some 40km relative to the block containing West Timor, the Savu Sea and Alor Island (see Fig. 1.3.3.3). Therefore, linking the above 50km of shortening in the arc, directly north of the collision/suture zone, with the 40km of crustal block movement, accounts for approximately 90km between a fixed position in the South Banda Sea and the Australian para-autochthon.

The value of 90km is probably a minimum when translation of terrain by strike-slip and subduction erosion is considered.



VERTICAL = HORIZONTAL SCALE

Fig. 1.4.1.3 Schematic diagram of the required shortening within the Timor region between the former collision zone and the volcanic arc

The amount of shortening due to subduction erosion can not be estimated but may have been significant, especially prior to the final collision and formation of the suture zone, when low density, incompetent, bathyal sediments would have been entering the subduction zone. This factor may in part account for the lack of rise deposits found on Timor.

The lateral translation of crustal blocks, due to strike-slip activity, is indicated by marine geophysical data. As already mentioned (section 1.3.2) there is evidence of strike-slip faulting some 10-15km off-shore of north East Timor. This fault zone can be followed bathymetrically south of the island of Kisar, and the Leti and Sermata island groups. There are correspondingly strong bathymetric lows to the north of these islands. The gravity, magnetic and seismic data indicate that these islands are part of the Australian sedimentary allochthon. Few workers have visited these islands recently, but early reports by Dutch geologists (see Van Bemmelen 1949) indicate the close geological affinity of these islands to units found on Timor. For example, the island of Leti is described as having a core of three or more E-W trending belts, consisting of steeply, northward, dipping strata and that metamorphism increases south to north. The southern belt is comprised of hardly altered, Permian sediments with brachiopods, fusilinids, trilobites, gastropods and crinoidal limestones. The central belt consists of phyllites, quartzites and crinoidal limestones. The northern belt includes a range of basic eruptive rocks (amphibolites, chlorite schists, diabase and tuff). In the far north a serpentinite mass occurs. The above description could, with little alteration, be applied to Timor and especially to the Aileu Formation. These islands rise steeply and abruptly from the Timor Sea, are only some 30km wide, north to south, and are bordered by deep and narrow submarine troughs. Additionally, examination of regional maps indicates that these island groups are arranged en-echelon to the trend of the Outer Banda Arc, having been apparently rotated 10-20km in a clockwise sense. Therefore, these islands may have been ruptured from the Timor region at the early stages of a right-lateral collision (the question of the sense of lateral movement, and associated plate movements will be discussed in section 3.2.1).

The total amount of shortening associated with translation of the islands to the east of Timor, can not be measured, but a minimum of 30-40km is suggested by the latitudinal width of the islands. Consequently, the total shortening between Wetar and the para-autochthon could be increased to 120km. This leaves some 100km of shortening required between the collision/suture zone and the present-day tectonic front situated just north of the Timor Trough.

This 100km is accommodated by overthrusting and stacking of part of the sedimentary allochthon and para-autochthon below Timor and by foreland thrust development and imbrication south of the para-autochthon to the Timor Trough.

Therefore, from north of Wetar to the present-day tectonic front, all of the necessary attenuation, of approximately 220km, can be accounted for within the upper 35km of the crust. This is the case for both models one and two. The real difficulty, when considering the collision in the Timor region, is accounting for the northward movement of the Australian plate below 35km.

Models produced by other workers either state, or imply, that the collision and formation of the suture was due to Australian continental crustal material being driven into the subduction zone. However, continental crustal material may subduct to depths of circa 60km, if part of it is of intermediate or meta-basic type, that is, of an overall density comparable to oceanic crust (see 1.4.4). In the Timor region, with a convergence rate of 7.5cm/yr, subduction would have stopped approximately 850,000 years ago. This leaves a short-fall of approximately 160km in accounting for the 220km northward displacement of the Australian plate.

This short-fall can be accounted for in two parts. Firstly, in the initial stages of the collision, the distance between the inner volcanic arc and the suture/collision zone was approximately 150km (Fig.1.4.5.1), and the suture/collision zone has now moved northward by approximately 120km. Most importantly, the steep Benioff zone, which now underlies the north coast of Timor, means that the leading edge of the Australian lithospheric plate has moved northward by approximately 120km. It should be borne in mind that 120km is a minimum figure based upon the measurable, and hypothesised, shortening within the upper 35km discussed at the start of this section.

Secondly, taking the 120km value, together with the probable amount of allowable subduction (60km), leaves a shortfall of approximately 40-50km in accounting for the northwards movement of the Australian lithosphere. There are three possible mechanisms that could account for this:-

1) the movement has been transferred across the whole of the Banda Sea region;

2) the Australian lithospheric plate has ruptured in the subduction zone below 60km, followed by a reversal of subduction polarity, allowing the South Banda Sea to subduct southwards;

3) that the original suture/collision zone was 40-50km further south than already described.

The first mechanism will be discussed in detail in Chapter 3.2, when the effect of the collision and continuing convergence is considered. Here, only mechanisms that can fully account for the collision and convergence within the Timor region will be discussed.

The second mechanism, that the Australian lithospheric plate has ruptured allowing subduction polarity reversal, is plausible. Price and Audley-Charles(1984) invoked this method to explain the effects of the convergence of the Australian plate, and the known geology of Timor. They attempted to account for approximately 140km of shortening by rupturing the Australian lithosphere, and subducting southwards the South Banda Sea via the Wetar Thrust. In this mechanism the Australian lithospheric plate is totally ruptured by hydraulic fracture, thereby creating sufficient space for the later subduction of 120-140km of the South Banda Sea. However, the present study only needs to account for 40-50km of subduction to the south, probably related to the 40km northward movement of the Timor/Wetar Strait/Wetar Island crustal block, which may have taken place along a low angle thrust zone within the upper 35km. If only 40-50km of movement is required, then a partial rupture, directly below the north coast of Timor, might suffice. This rupture may be caused by the positive buoyancy of the Australian continental material rupturing the subducting plate at the leading edge of the lithospheric plate. The disruption may occur at the boundary between intermediate and continental crustal materials. The cool, dense oceanic lithosphere below the rupture would continue to sink, which, coupled with the isostatic rebound of the continental crust, would expand the rupture. Model 1 allows for this rupture and subduction of South Banda Sea material in the region of polygon 20 (3.330g/cc).

The third mechanism simply requires that the position of the original collision, and therefore the pre-collision subduction trench, be some 40-50km further south than that already deduced from examination of attenuation in the upper crust. If the original Benioff zone was inclined at 45 degrees, the entire movement of the Australian lithosphere can be accounted for. It is interesting to note that this method places the original collision position in the same vicinity as the 'preferred location of the hypothetical subduction trench' calculated by Johnston and Bowin (1981). These authors used DSDP hole 262 environmental data to determine the horizontal distances within the collision zone and combined these data with plate motions to derive an estimate of the surface width of the subduction zone through time.

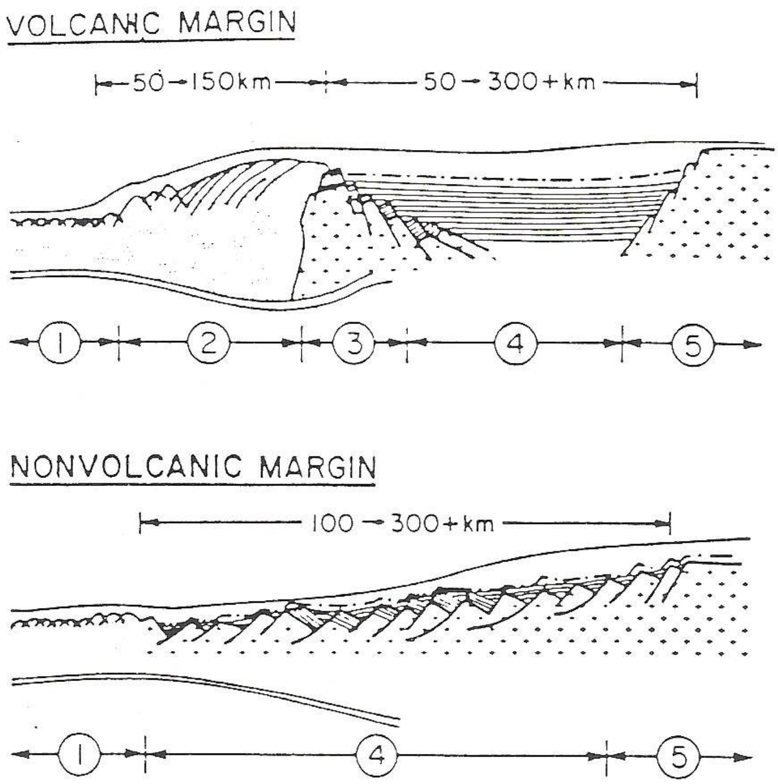
If all of the convergence of the Australian plate has been accommodated within the Timor region, then the third mechanism is preferred. This mechanism will be expanded upon in the next section.

1.4.6 DISCUSSION AND CONCLUSIONS ON THE TIMOR REGION.

In this section an attempt will be made to outline the development of the Timor region based upon the known geology and the modelling discussed in the preceding sections.

The northwards drift of Australia during the Cenozoic has been documented by Smith et al(1981). Prior to the Late Miocene, the Australian para-autochthonous rocks were deposited in moderate to deep water, while the allochthonous units were deposited in shallow water. This difference can be explained by proposing that following Early Jurassic rifting the allochthonous sedimentary units formed the leading edge of the Australian passive margin, and that the para-autochthon was deposited on the southern margin of the allochthonous edge, and in an adjacent intracratonic basin. The configuration can be likened to the distribution of platforms and basins on the present Australian Shelf, where, for example, the Sahul Platform, directly south of Timor, separates the Timor Trough from the Malita/Calder Graben system.

Mutter et al (1988) have examined passive margins around the world and consider that there are two broad morpho-genetic types, the classic non-volcanic and volcanic margins (Fig.1.4.6.1). They report that most of the present Australian margin is of the volcanic type, including the Scott and Exmouth Plateaus to the south-west of Timor. A volcanic margin converging on the Timor subduction zone 3-4my ago may adequately explain the observed geology and the preferred gravity model (two) used in this study.



Comparison of the typical structural elements of "volcanic" and "nonvolcanic" margins.

1, the normal thickness oceanic crust; 2, the thick volcanic succession associated with the continent-ocean boundary of volcanic margins of which the seaward dipping units form the upper sequence; 3, a structural high in continental crust that often occurs adjacent to the thick volcanic succession; 4, thinned, subsided continental crust; 5, unstretched continental crust. The dot-dash line marks the stratigraphic level of breakup. Parallel ruled regions indicate sediments.

FIGURE 1.4.6.1 Volcanic and Non-volcanic margins.
From Mutter et al. 1988, figure 7

Mutter et al(1988) list six features of volcanic margins:-

1) up to 20km of igneous crust separating continental from oceanic crusts;

2) a typical width of 70km for the igneous crust;

3) seaward dipping reflectors, associated with the igneous crust, are coextensive with the oldest of the seafloor spreading magnetic lineations;

4) the furthest seaward extent of the dipping reflectors and igneous crust marks the transition to oceanic crust;

5) the igneous crust was emplaced within, or adjacent to, a major structural high of the continental crust which may mark the boundary of a pre-breakup basin;

6) the upper continental crust shows little or no evidence of extensional faulting associated with spreading.

The igneous crust is created by lateral temperature gradients, causing small-scale convection in the upper mantle at the time of continental rifting. The seaward dipping reflectors and igneous crust, occur on the flanks of major structural highs that were formed during tectonism that pre-dates the emplacement of the thick basaltic crust, and the onset of seafloor spreading. As spreading continues the lateral temperature gradients decrease, causing the mantle adjacent to the continental margin to cool, thereby halting the convective process. Continuing spreading causes the margin to subside, but the earlier convective episode has already caused a thinning of the continental lithosphere. This results in excessive uplift of the rift-flank, in excess of that caused by passive stretching, and may lead to the continent/oceanic boundary being anomalously shallow well into the spreading history of the margin. For example, the Outer Voring Plateau, a volcanic margin off Norway, has probably subsided only 1500m in the 58My since spreading commenced.

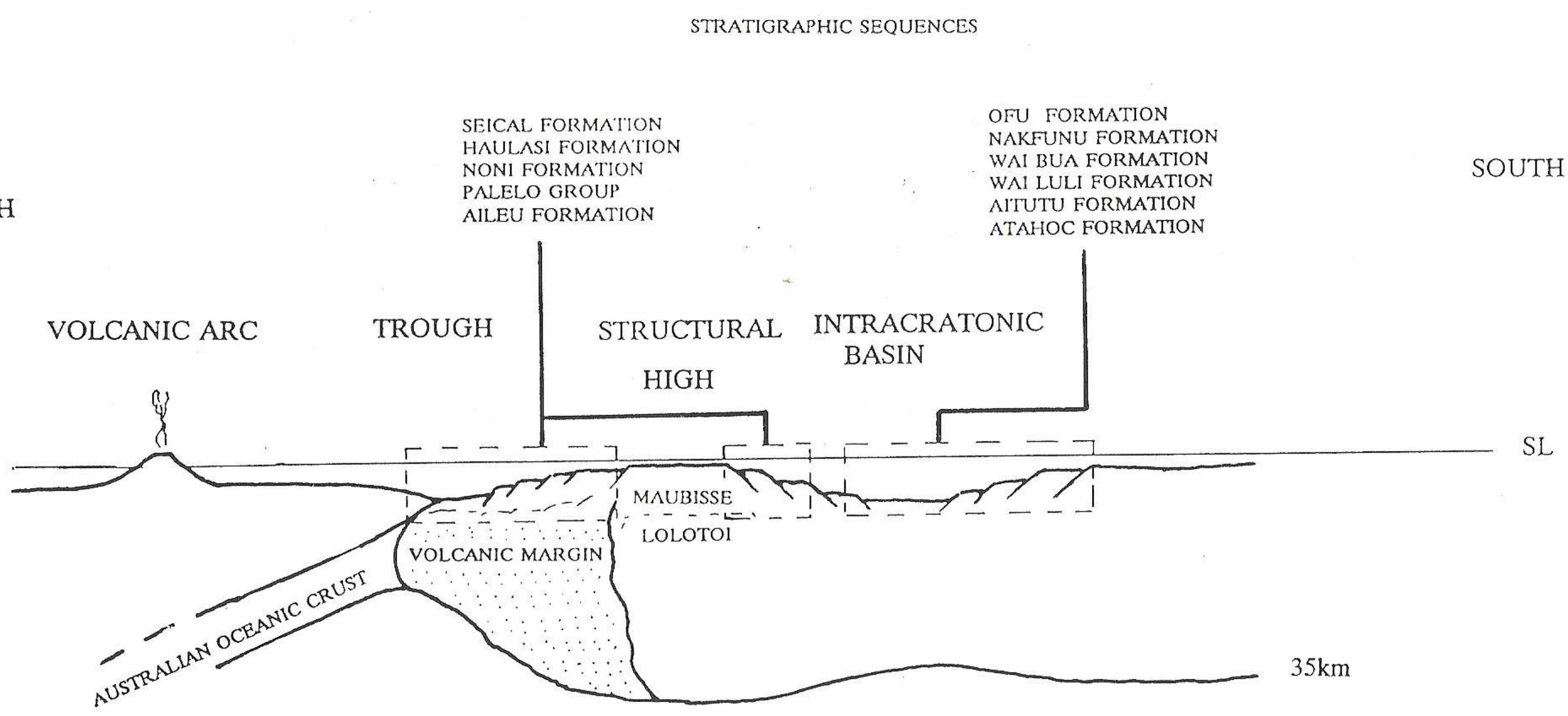


FIG. 1.4.6.2 THE AUSTRALIAN MARGIN DURING THE OLIGOCENE

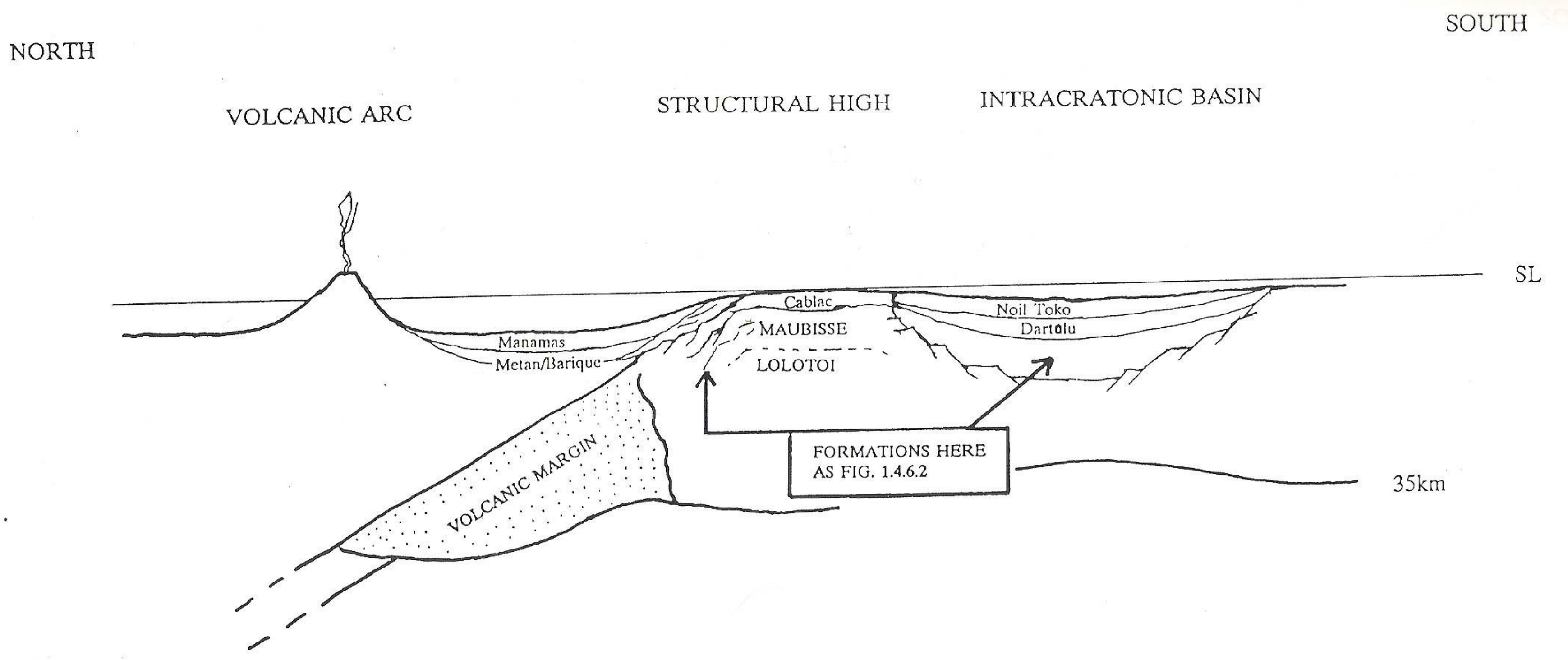


FIG. 1.4.6.3 The Australian Margin during the Early Pliocene

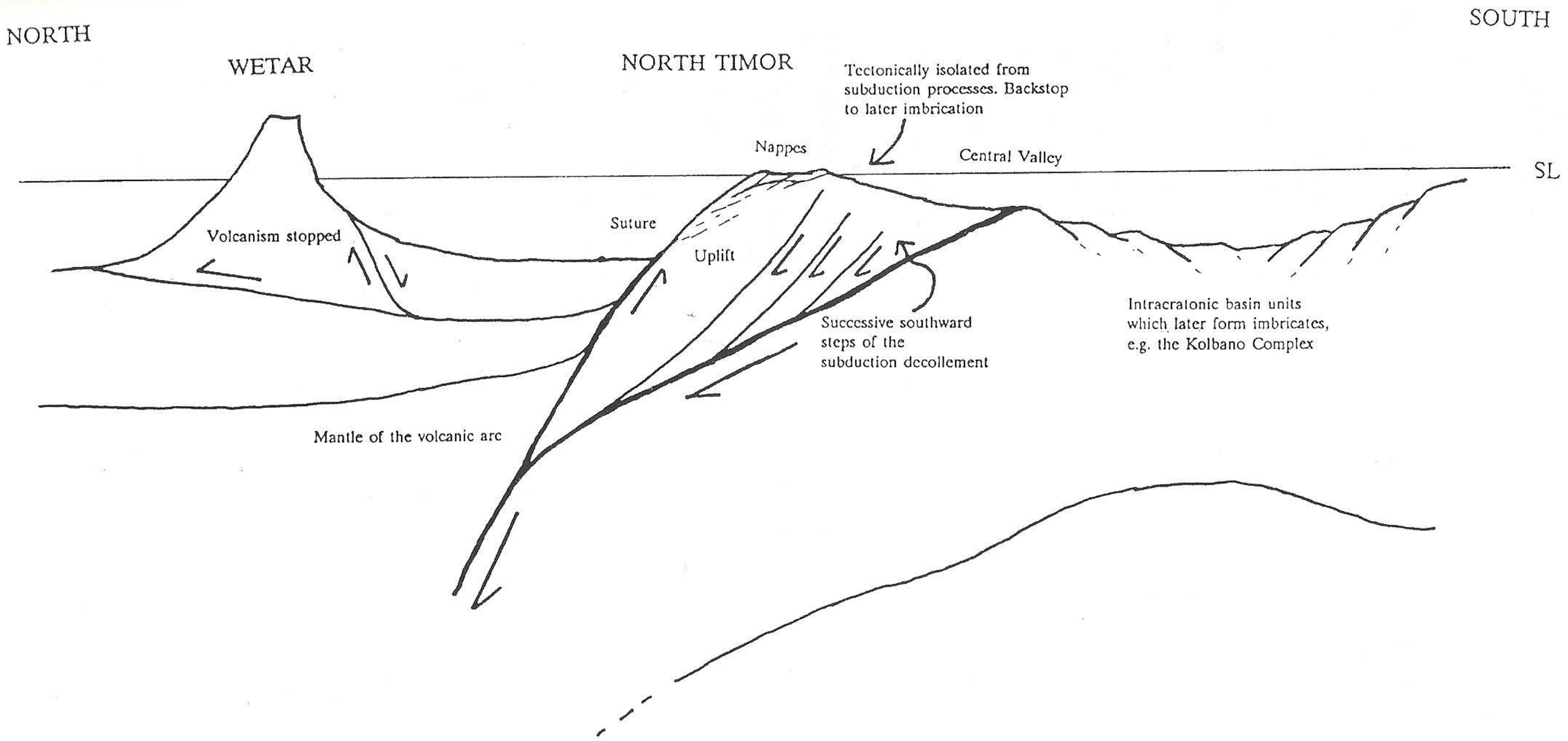


FIG. 1.4.6.4 EVENTS FOLLOWING SUTURING

Figure 1.4.6.2 is the proposed configuration of units during the Oligocene when the northward converging Australian plate was subducting oceanic material under the oceanic 'South Banda Sea'. The Lolotoi/Mutis Complex is shown forming the upper crustal basement to the Maubisse Formation in the structural high bordering the Australian continental margin. Adjacent to this high are the other sedimentary allochthonous units. The Seical Formation is the youngest unit and is shown having been deposited either side of the structural high. It is not clear whether this high was a site of non-deposition, but the disposition of the Maubisse and Lolotoi/Mutis Complexes on Timor indicate that they had little or no cover sequences prior to their thrust emplacement after collision. The structural high also solves a provenance problem for some of the para-autochthonous units which show derivation of sediments from the north.

The present configuration of structural highs and grabens/basins on the Australian Shelf is a long established structural style. For example, Bird(1985), commenting on the Permian of the Australian Shelf and Timor, interpreted both areas as part of the same continental province, and that a number of positive plateaus were separated from each other by subsiding basins. The basins accumulated large thicknesses of clastic sediments (e.g. Bisane Formation), while the highs were the depositional sites for carbonates (Maubisse Formation). Further commenting on the para-autochthonous Bisane, Bird(1985) states that the clastic sediments are moderately mature and were in part derived from local sources and from a continental block to the north. This block may have been the Lolotoi/Mutis high (or a lateral equivalent). Cook(1984 and 1985) examined the Triassic rocks of the Australian Shelf and Timor, concluding that the source areas were uplifted basement blocks on the Australian Shelf, and that Timor lay on the outer part of the continental margin. Similarly, Barkham(1987), reporting on his studies of the Permo-Triassic of Timor, states that the Maubisse (allochthonous) and Atahoc plus Cribas and Aitutu Formations (para-autochthonous) appear to have been deposited in a similar tectonic setting/area. These units contain pillow lavas that were probably erupted during an abortive rifting episode. Barkham speculates that this earlier attempt at rifting formed horsts on which shallow water carbonates were deposited, and grabens in which deep water clastics accumulated.

It therefore seems probable that the allochthonous and para-autochthonous units now emplaced on Timor were, prior to the rifting of the Australian continent, adjacent to one another. However, the location of this rifting is crucial to the understanding of the various models invoked to explain the juxtaposition of the allochthon and para-autochthon on present-day Timor.

One model proposes that allochthonous Timor was rifted northward during the Jurassic, away from the para-autochthon. This rifted mass later collided with the SE Asian margin, subsequently forming part of the volcanic arc that collided with the Australian para-autochthon 3my ago (e.g. Barber et al,1977; Barber 1979; Hamilton 1979; etc). Problems with this model include the lack of evidence in the allochthonous units of multi-phase deformation, resulting from a double collision, and the thinness, north to south, of the allochthon exposed on Timor, coupled with the necessary length (2000km) of the allochthon around the present Outer arc. Simply, this model requires an unknown width of Australian Shelf to rift from the remainder, travel north to collide with another boundary, and then to be rifted once again as a very thin, but extremely long, margin to a volcanic arc, which was subsequently reunited with the Australian Shelf.

Other models involve a) primarily vertical movements on Timor following the Late Miocene/Early Pliocene collision (e.g. Chamalaun and Grady,1978) and b) thrusting and duplication of Australian crust by wrench faulting, resulting from oblique collision between the Banda Arc and the Australian Shelf (Charlton, 1989). Essentially, both these models require that the northern Timor allochthonous units formed the leading edge of the

Australian margin at the time of collision. However, the duplication of Australian continental units, north to south across Timor, would appear inconsistent with the model of Timor primarily involving vertical movements, while the oblique collision model does account for the known structural style and distribution of units. Both thrusting and large vertical displacements have been observed on Timor, and both models require the allochthonous units of northern Timor to have been adjacent at all times to the Australian para-autochthon.

Audley-Charles(1968) originally used the term 'allochthonous' for those units that were not part of the Australian plate during the post-rifting stage. However, an allochthonous unit by definition is one that has travelled a considerable distance from its site of deposition. Certainly, the thrust sheets of Lolotoi, Maubisse and Cablac have moved southward some 50km since the Late Miocene/Early Pliocene and can still be classified as allochthonous. This may not be the case for some of the root zones to the thrust sheets. However, in general terms, and attempting to avoid any worthless semantic arguments, the term 'allochthonous' will continue to be applied to the thrusted sheets of the Australian continental margin and their root zones. This is compatible with all previous uses of the term in this study.

Figure 1.4.6.3 shows the supposed distribution of units at the time of collision in the Timor area. The igneous crustal complex has already been subducted, possibly leaving the allochthonous Palelo Group at the surface (suggestion made by M.G.Audley-Charles pers.com.1989). The structural high of the Australian margin is being depressed into the subduction zone, thereby allowing the deposition of the platform carbonates of the Cablac Formation on top of the Maubisse and Lolotoi/Mutis units. The subduction of the Australian igneous crust, and rise deposits, caused the hydration of the mantle of the arc. However, volcanism continued, which resulted in the deposition of the Metan, Barique and Manamas volcanics. Possibly, the 'high' caused by the Lolotoi and Cablac, was not a continuous rampart, barring sediment transport from the inter arc gap to the Australian Shelf. Transport of volcanic detritus through channels in the 'high' would explain the presence of tuffs in the Noil Toko, Batuputih and Noel Formations of the para-autochthon and autochthon.

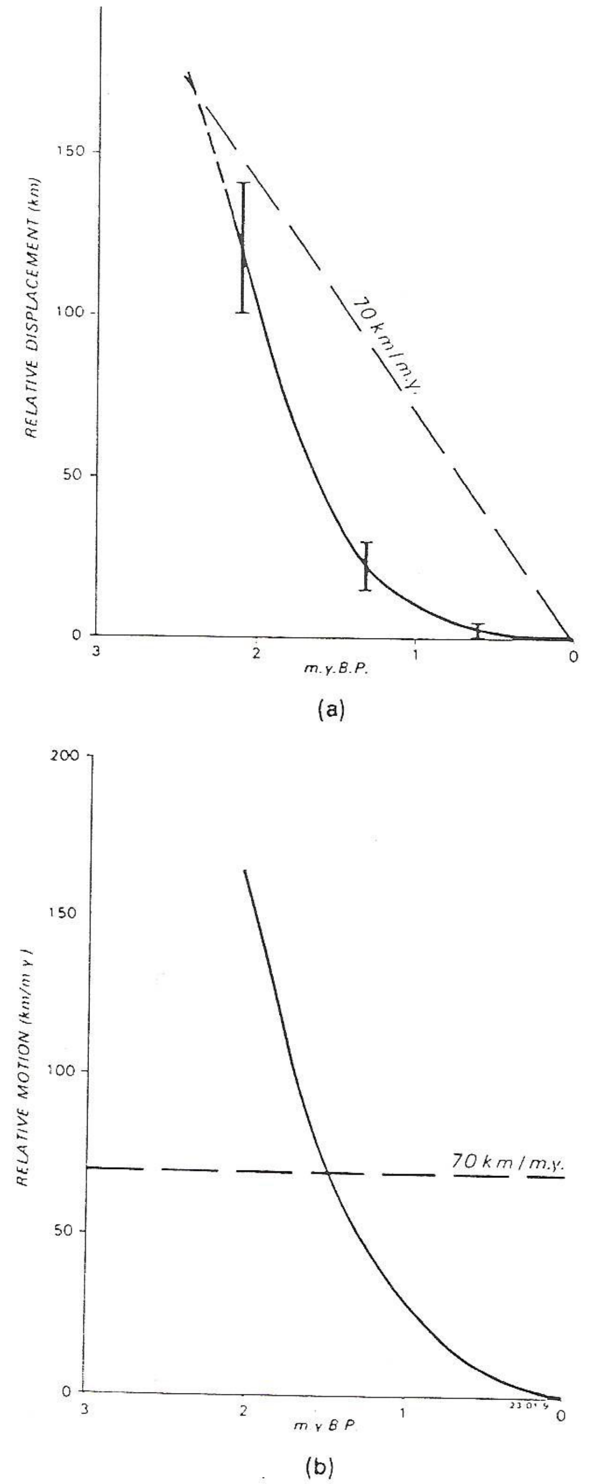
The Batuputih Formation was deposited in deep water immediately after the collision. This deep water environment may be explained by proposing that in the initial stages of collision the 'high', and regions south on the shelf, were depressed. After this initial depression there was uplift of Timor, resulting in the shallow water deposition of the autochthon. It is probable that different areas of the colliding margin have varying uplift histories, possibly relating to the original configuration of the 'high'. The distribution of thrust sheets on Timor also suggests considerable variation in the original deposition of the Cablac Formation (see discussion on the Bouguer anomaly map, section 5.1).

At, or soon after, the time of the initial collision, volcanic activity stopped on Atauro and Wetar, an event probably linked to the northward migration of the Timor/Wetar Strait/Wetar Island crustal block, which may have displaced the magma conduits from their source chambers. This movement of this eastern crustal block, suggests that this region collided with the subduction zone before the western block.

As the collision proceeded, leading segments of the 'high' may have been strike-slipped eastwards to form Kisar Island and the Leti and Sermata groups. This implies that the collision had a right-lateral sense (see section 1.3.3). This observation agrees with the claims made by Vening Meinesz(1954), Katili(1970), Cardwell and Isaacs(1978), Bowin et al(1980) and Johnston and Bowin(1981), that the direction of convergence between the Australian-Indian Ocean plate and the Southeast Asia plate was north-northwest. It should be noted that all of the structures, lineaments and inferred directions of movement considered probable in this study, can be accounted for by either left or right lateral systems. The exception is the eastwards strike-slip of Kisar etc., which can only have taken place in a right-lateral system.

The stress, and resulting strain, increased as collision continued, causing the leading edges of the Australian margin and opposing volcanic arc to become tectonically mixed. This probably occurred at all levels within the collision zone, and is now demonstrated by some of the sedimentary allochthonous sheets on Timor being structurally in contact with volcanic meta-basics. Having already been elevated by thrusting, some of these thrust sheets underwent gravity-sliding once northern Timor started to rebound isostatically. In these cases the decollement medium may have been the bathyal lutites and clays of the former Australian rise. R.Harris (pers.com.1989) speculates that these rise deposits may now be represented by the Bobonaro Scaly Clay. He considers that the Bobonaro was part of a melange wedge prior to the collision that was subsequently disrupted and transported. The collision may have caused the shallow, melange wedge to form olistostromes, which moved southwards into the relatively deeper water caused by the depression of the 'high'. Later compression, tectonic mixing of terrains and overthrusting southwards, would have further disrupted the olistostrome/melange deposits. Parts may have become buried by overthrusts, or caught up in the later imbrication of the para-autochthon, and are now emerging at the surface as shale diapirs/mud volcanoes on Timor (and throughout the Outer Arc).

Immediately prior to the suturing of the Australian sedimentary allochthon with the margins of the volcanic arc, there may have been a considerable steepening of the subduction zone. After suturing the subduction decollement would have to step southwards to allow continuing subduction. The first step may have been the largest, due to the steep suture, and may therefore have underplated a large volume of the allochthon, and the following para-autochthon, to form the deeper levels of the upper crust of northern Timor (Fig.1.4.6.4). This would tectonically isolate northern Timor, and account for the lack of imbricate wedges anywhere on Timor north of the Central Valley in West Timor. Therefore, the back-stop to the imbricate wedge becomes the isolated, southern edge, of the northern allochthonous section.



(a) Horizontal displacement and (b) corresponding motion between the tectonic front of the subduction zone and the DSDP location on Australian continental crust in the vicinity of western Timor.

IGURE 1.4.6.5 Figure 9 from Johnston and Bowin(1981)

The present northern allochthonous section was formed by successive southwards steps of the subduction decollement, resulting in the duplication of Australian continental units, north to south, across Timor.

In the volcanic arc, the leading edge of the lower crust may have been shortened by northwards thrusting, and thickening, by underplating. Concurrently, the mantle north of the suture may have accommodated the shortening by thickening, and also by the anti-clockwise, vertical rotation and up-thrusting of a nascent, obducting, slab. This slab may have been active for much of the last 3my, resulting in the later southwards thrusting of the Manamas and Ultra-basic Formations in West Timor. Additionally, the more recent upward movement of the southern margins of the volcanic arc may be due to the fact that it is sutured to the isostatically-rebounding margin of continental Australia. Obduction and passive vertical movement would explain why the south of the Wetar Strait is elevated considerably beyond the isostatic norm, while the northern half has subsided, allowing the formation of the half-graben in-filled with recent sediments.

The normally faulted boundary between the Wetar Strait and Wetar Island, allows the sinking of the strait and the rising of the island. The sinking of the strait is peculiar, as is the normally faulted boundary to the north, in a region where uplift of the inner and outer arcs is taking place. However, the Wetar Strait was placed out of isostatic equilibrium by the collision, and is therefore naturally prone to sink. However, this whole region was under compression, and so extensional normal faults, of the size seen at the northern side of the Wetar Strait, should be unlikely. It is speculated that the reason for its existence is the present-day stress field across the whole of the Banda Sea region. Simply, following collision around the arc, the stress caused by the convergence of the Indo-Australian, Southeast Asia and Pacific plates upon the Banda Sea region has now created a left-lateral strain from Seram in the north to Timor in the south. The major compressional axis is orientated N-S and the extensional axis E-W. The extensional stress has resulted in the Weber Deep and Aru Trough. Geophysical data indicates that extension is presently dominant in the Timor region, which may result from the extensional strain being transmitted from the Weber Deep region westward around the arc. This most recent of stress regimes would enable the formation of the large normal fault in the north of the Wetar Strait. This hypothesis is closely linked to the reversal of right, to left, lateral strain systems in the Timor region, and will be discussed in greater detail section 3.2.1.

In conclusion, after collision the East Timor region experienced the northwards movement of the East Timor crustal block, the strike-slipping of Kisar etc., attenuation of the leading edge of the volcanic arc and the initiation of an obducting mantle slab. After the suturing of the collision zone, the decollement steps southwards, removing the north of Timor from the subduction process and effectively isolating a crustal block containing Wetar island, Wetar Strait and northern Timor. Subduction continues to the south of Timor with the imbrication of units similar to the Kolbano Complex. However, the rate of relative movement of the subducting plate decreases with time as the buoyancy effect of the Australian continental crust, overcomes the negative buoyancy of the already subducted oceanic plate. This decrease in relative motion has been documented by Johnston and Bowin (1981) (see Fig.1.4.6.5).

It has been demonstrated that all of the necessary shortening within the upper crust can account for the approximately 220km of convergence of Australia toward the South Banda Sea. Also, if the collision took place because Australian continental crust arrived at the subduction zone 3my ago, and if it is accepted that only 55 to 60km of subduction of continental crust took place, then the rest of the convergence of the Australian plate must be by means other than normal subduction processes. Figure 1.4.1.3 shows the former position of the suture/collision zone relative to present-day positions, and demonstrates that the 220km of movement of the Australian plate can be accounted for by horizontal convergence and steepening of the Benioff zone. It has been estimated that approximately 120km of shortening has taken place between the former position of the suture/collision zone and the old volcanic arc position. However, the horizontal convergence proposal requires 160km of shortening leaving a shortfall of 40km.

This shortfall is probably linked to the former position of the suture/collision zone, which is based on the supposition that some 55 to 60km of continental crust can be subducted before buoyancy forces halt the process. If continental crust can be forced deeper down a subduction zone, then the shortfall of 40km decreases by that amount.

There are other, possibly more plausible, methods of reducing the missing 40km. For example, the amount of strike-slip faulting of terrains, the degree of tectonic erosion, the extent of compressional overthrusting and thickening can all be increased by relatively small amounts to account for the 40km. Also, all of the models discussed have been drawn parallel to the main compressional axis across the Timor region, and none of the calculations have allowed for extensive shortening in an oblique collision setting. The Timor collision was probably not as oblique as that on Taiwan, but many of the inferred processes and resulting attenuation seen on the latter island, between the volcanic arc and continental margin, may be analogous (see section 3.1.3 - Ophiolite Terrains).

While the Australian plate was driving horizontally northward, the north of Timor was experiencing uplift, probably resulting from two processes. The first is isostatic rebound of the continental margin. The second is the result of the steepening of the Benioff zone due to the horizontal, northward movement of the Australian plate. The steepening may have caused units within the collision zone, and north Timor, to rotate vertically in an anticlockwise sense (viewed from the west). The two processes would force blocks in the upper levels of the crust to move vertically along normal faults, giving the typical structural style of northern Timor, where extensional vertical tectonism overprints the earlier compressional thrusting.

As northern Timor was raised, large quantities of detritus would be produced and deposited as molasse in the south. This influx of molasse, plus the imbrication and stacking of the para-autochthon, would cause a downward flexure in the continental crust of southern Timor, and the Timor Trough, as these regions attempt to maintain isostatic equilibrium.

In the presented model, the Timor Trough is now a foreland basin, with the former surface traces of the subduction zones now lying further north under foreland thrust sheets and units formed by subduction driven imbrication.

PART TWO

THE
TANIMBAR AND
KAI ISLANDS
EASTERN INDONESIA

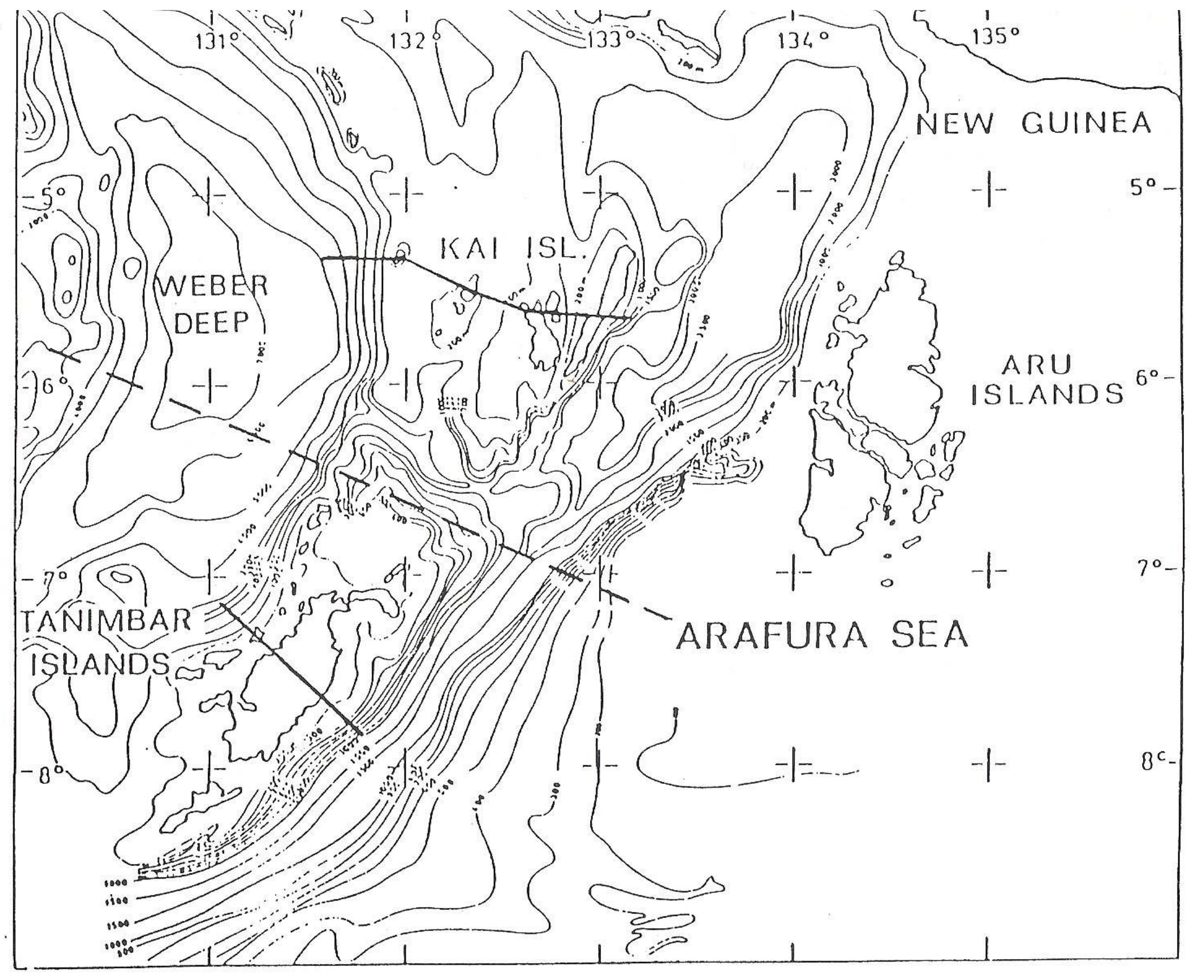
CHAPTER 2.1

GEOGRAPHICAL AND GEOLOGICAL DESCRIPTION OF THE TANIMBAR AND KAI ISLANDS

2.1.1 GEOGRAPHICAL SETTING

The Tanimbar and Kai islands are the emergent parts of a broad, generally submarine plateau which lies between the Weber Deep to the west and the Arafura Sea to the east (Fig.2.1.1.1) and which forms a part of the Banda forearc, the site of the collision between the Australian and South-east Asian plates. The plateau is divided into two parts (the Kai and Tanimbar segments) by a narrow NW-SE trending trough which cuts it at right angles to strike between 6^o and 7^{o}S. The Weber Deep, which lies west of the plateau and separates it from the small volcanic islands of the inner arc, is a forearc basin which reaches depths of more than 7000m.

The continental shelf of Australia and New Guinea lies at depths in the region of 200m, beneath the Arafura Sea south and east of Tanimbar. East of Kai, it emerges above sea level to form the Aru Islands. The Tanimbar Trough, which separates the Tanimbar section of the forearc plateau from the shelf, has a maximum depth of about 1500m and is about 50km wide (between 1000m contours) east of Tanimbar. To the northeast the water deepens into the 3500m deep Aru Trough, between the Kai and Aru Islands. The junction between the Aru and Tanimbar Troughs coincides roughly with the trough between Kai and Tanimbar; the latter feature does not appear to extend eastwards into the Arafura Sea.



—— model profile lines this survey.
— — — BGR model profile line (Schluter and Fritsch,1985).

FIGURE 2.1.1.1 Bathymetric locality map together with gravity model profile lines

2.1.1.1 TANIMBAR

Jamdena, the main island of the Tanimbar group, is elongated NNE to SSW, sub-parallel to the Tanimbar Trough, with a maximum length of about 120Km and a maximum breadth of 60Km (Fig 2.1.1.1). It has a moderately gentle topography, with the highest areas bordering the east coast, where a series of ridges runs sub-parallel to the coast from Ilgnei, in the south, to Arma in the north. Rivers flow westwards from these ridges to the west coast across a broad flood-plain, finally entering the sea in Selat Jamdena. Average elevation of the flood-plain is 50m; the rivers are deeply incised in places, suggesting rather recent elevation. From half-way across Jamdena the rivers are only a few metres above sea-level and meander sluggishly, the meanders being geologically controlled. During the dry-season (March/April - Nov/December) many sections of the river beds are dry; flash-floods occur in the wet season.

The eastern ridges are considered to be still rising, since the river courses through them have many falls and traps and flow is probably controlled by differentially uplifted topographic blocks. Some dry river beds are full of ironstones derived from the mud volcanoes that are scattered across Jamdena. Most of the mud volcanoes are inactive but their presence can be detected by the type of soil, which is dark grey with fragments of ironstone and a variety of limestones. Another common indicator of mud volcanism is the presence of round, red-brown spherules of limonite, radius 1-3mm found scattered across flat patches on jungle paths. These may be formed by a chemical reaction between rain water and an iron rich soil, presumably because the neutral/acid rain water changes the pH of the soil. This results in the precipitation of limonite which nucleates around soil particles, the spherules forming as they are washed around on the flat paths. Vegetation is another clue to the presence of mud volcanoes; most of Jamdena is covered by dense, dark green, primal jungle, but in areas of mud volcanism this gives way to a thick undergrowth of spiky bushes with few large trees.

To the northwest of Jamdena lies a crescent of smaller islands ('the inner islands'), separated from the mainland by the shallow water Selat (Strait) Jamdena. The latter is being infilled by sediment from Jamdena and may also be undergoing uplift. As a consequence, water depths are decreasing, at least as far as can be judged from comparing maps prepared during the Dutch colonial era with present-day observations, and new islands seem to have appeared both in the north and the south of the strait. Selat Jamdena is also the site of the most active present-day mud volcanoes. The 'inner islands' mark the western edge of the Tanimbar section of the plateau, beyond which the sea floor descends rapidly to the Weber Deep, with a gradient much steeper than that off the east coast of Jamdena into the Tanimbar Trough.

Saumlaki, the main town of Jamdena, has a permanent population of a few thousand, increased periodically by people from surrounding villages visiting for administrative, commercial and social reasons. There are two hotels, a post-office, electricity (overnight from 1800 to 0630), pumped water, a market, numerous shops, a fuel store and petrol station, a deep-water anchorage, an airfield which is being extended, an hospital run by the Catholic Mission and all the normal administrative offices (Camat, Police, Army, Social-Police). Most of the people of Jamdena are Christian but there are new Muslim villages situated in the north of the 'inner islands'.

Saumlaki is linked to the rest of Indonesia by twice weekly Merpati flights from Ambon via Tual in the Kai group. Communications with the outside world have much improved since 1986. There is now a satellite television antenna which serves the town and the surrounding villages, and coverage will be gradually extended to the rest of the island. Telegrams can now be sent and international telephone calls made via satellite. Saumlaki now has better communications with London and Jakarta than it does with villages only 10km away, the local subsidised ferry service being infrequent and irregular.

The country surrounding Saumlaki for a radius of 2-3km, and along the only road, is cultivated and in parts is being taken over for cattle-ranching. All villages in the remainder of the Tanimbars are situated on the coast where the inhabitants make a living from fishing, hunting, logging and growing coconuts for copra. The interior of Jamdena is covered in primal jungle criss-crossed by jungle paths. There are no reliable maps of these paths; local people will know where a path goes to and from but cannot be relied upon to know where they are at any point along it. Distances are measured in days taken to walk from one point to another, a system which can mislead slow-walking Europeans. The best guides to the interior are the hunters who spend most of their time tracking wild water-buffalo and pigs.

Nearly all of the villages have a small shop which sells luxury goods such as Coca Cola, cigarettes and batteries. Staple foods cannot be bought in most villages and water is often in short supply. Survey teams have to buy all their goods in Saumlaki and must ensure that they have adequate water supplies. The poorest villages are along the west coast of Jamdena and on some of the 'inner islands'. The smaller 'inner islands' are used as gardens which many villagers from the larger islands and Jamdena visit during the dry-season. This activity, together with hunting and logging expeditions into the jungle, can mean that villages are virtually deserted except for children, old people and a few able-bodied folk left to run things. This 'migration' to other areas is also possibly a response to the lack of water in some villages by the end of the dry-season.

The population of the Tanimbar Islands is increasing rapidly due to better health care and education. Numbers will further increase in 1988 when the first stage of the 'transmigrasi' plan will settle people from Java on Jamdena, reportedly between Atubul and Amdasa. The influx of more competent farmers will place strains on the available land and water supplies and it is possible that in a short time cultivation will have to be extended to the interior jungle areas. Already loggers are using the new road to cut deep into the jungle and the cattle-ranching around Saumlaki has turned the area into a grassland. Eventually the jungle will be stripped from Jamdena and the landscape will become savanna, like Timor which has a similar climate.

2.1.1.2 Kai

The Kai Islands (Fig 2.1.1.1) are situated about 300km NNE of the Tanimbars, the most easterly being Kai Besar, a rugged NNE to SSW elongated island with elevations up to 800m. To the east of Kai Besar the sea floor drops steeply into the Aru Trough, while to the west the sea floor is relatively flat and shallow (circa 200m) as far as the islands of Kur and Fadol. The largest island of the Kai group, Kai Kecil, is separated from Kai Besar by Selat Nerong and, in sharp contrast to it, is generally flat and low-lying (50-100m).

The administrative centre of the group, Tual on Kai Kecil, has all the usual administrative offices, day-long electricity, pumped water, television, two or three hotels, a busy bus service to the outlying villages and a deep-water port which serves as a transhipment point to the smaller islands of the group. The airport, linked to Ambon by the Merpati flight which also connects with Saumlaki in the Tanimbars, lies about 3km from Tual. The road system on Kai Kecil is very good (compared with that on Jamdena) but is still not complete, with some villages accessible only by footpaths. Many of the roads across the island were built to reach the inland airfields used by the Japanese during World War 2. As in the Tanimbars, all villages are situated on the coast but the level of development is generally higher. Electricity supply is being extended north and south of Tual along the roads. Water supply is critical on Kai Kecil and at the end of the dry-season villagers commonly have to walk 5km for water. The lack of water and the particularly poor soil make cultivation very difficult. The island is formed almost entirely of raised coral, the soil being usually only a few centimeters thick and full of coral fragments. The raised coral islands off the west coast of Kai Kecil are mostly uninhabited because of lack of water.

Some 30km west of Kai Kecil lies a second group of raised coral platform islands which seldom exceed 50m in elevation. Pulau Taam, reaching to more than 130m, is an exception. The surrounding seas are treacherous, with large areas of shallow water covering reefs and sand bars. At low tide in some regions the villagers can be seen walking on top of exposed reefs 2.5km off-shore. There are only a few villages and no roads or other modern conveniences. The way of life is similar to that in the remote villages of the Tanimbar Group. At Tanjung Matot, a peninsula on the north-east coast of Tayandu, the largest island of this group, there is an active mud volcano. Further west still, at the edge of the Weber Deep, lie the islands of Kur, Fadol, Wonin and Manggur. These islands have undergone periodic uplift resulting in sharp scarps and level terraces. Wonin and Manggur consist entirely of coral reef, but Kur and Fadol have cores of high-grade metamorphic rocks overlain by Mesozoic and younger sediments.

Kai Besar is very different from the other islands in the group. It is elongated NNE to SSW and both high and rugged, rising steeply from the sea on all sides. The principle town of Elat is located half-way along the west coast. Like many towns in this region, Elat is being rapidly developed and many new facilities are being built or are planned. Two ferries operate across Selat Nerong between Tual and Elat; the strait is marked on the 1:250,000 maps as being everywhere deeper than 10m except for a few small areas adjacent to Kai Besar, with a central channel between 100 and 200m deep. However, at low-tide large areas half-way between Tual and Elat are above sea-level, which would seem to indicate that the strait is rising, at least in the region between the central channel and Kai Besar. In contrast, Kai Besar itself is reported to be sinking, as indicated by partially submerged coconut trees along parts of the coast.

2.1.2 THE HISTORY OF EXPLORATION

As in other island groups in Indonesia, the Dutch were the first westerners to carry out geological fieldwork in the Tanimbar Islands. A reconnaissance study by Verbeek(1908) covered the coastal areas where he noted raised reefs. He also noted that the interior had not then been visited by a European. Brouwer(1923) described Mesozoic and Tertiary sediments and made reference to mud volcanoes on Yamdena. Weber(1925, published in Umbgrove,1938) interpreted the geology of the island group as consisting of overthrusts of Mesozoic rocks over highly folded Tertiary rocks. The Tertiary sediments were interpreted as littoral and neritic. Weber also produced a complete stratigraphy from the Permian to Tertiary which was later criticised by Heim(1939), who stressed the influence of mud volcanic activity in the area and suggested that Weber had been incorrect to use mud volcano clasts in his stratigraphic scheme. The present author considers that, in regions where little detailed mapping has been done, it is reasonable to include mud volcano evidence in a stratigraphic scheme.

There was a hiatus in activity following WWII until the publication of a Preliminary Geologic Map by Sukardi and Sutrisno(1981). In 1986 a team from the University of London, the Free University of Amsterdam and the Geological Research and Development Centre (GRDC) conducted a reconnaissance survey, the aim of which was to determine the Cenozoic history of the island group (de Smet et al,1988). These results have been incorporated into the Snellius II Programme to determine tectonic movements rates for the Banda Arcs. In 1987 two members of the 1986 team returned to the Tanimbars together with personnel from GRDC to conduct a gravity and magnetic survey (Kaye and Milsom,1988) and a more detailed geological survey (Charlton,1988). This work was funded by Union Texas (South East Asia), under the aegis of the University Consortium for Geological Research in SE Asia. In 1989, further geological and geophysical surveys were conducted on both island groups.

2.1.3 STRATIGRAPHY OF THE TANIMBAR ISLANDS

Much of the following is based on the geological map of Sukardi and Sutrisno(1981) and reports by de Smet(1988), Charlton(1988), Kaye and Milsom(1988), Charlton, Barkham and de Smet(1989) and Kaye(1989).

The stratigraphy of the Tanimbar Islands is summarised in Figure 2.1.3.1.

TRIASSIC TO EARLY JURASSIC - consisting of cross-bedded, rippled, turbiditic sandstones, frequently with sole and tool marks on bedding planes, are found as ejecta from mud volcanoes in the Selat Yamdena region. The environment was probably shallowing upwards, from deep marine to marginal, or non-marine in the Early Jurassic, with rapid deposition from turbidity cuurents, sourced from a delta. Thicknesses for the Tanimbar area are unknown but comparable outcrops on Timor and sequences in boreholes on the Northwest Shelf of Australia are 100s of metres thick. These rocks are similar to the deltaic turbidites of the Babulu Formation in West Timor, which is a lateral equivalent of the Aitutu Formation and the youger part of the Maubisse Formation.

STRATIGRAPHY OF THE TANIMBAR ISLANDS

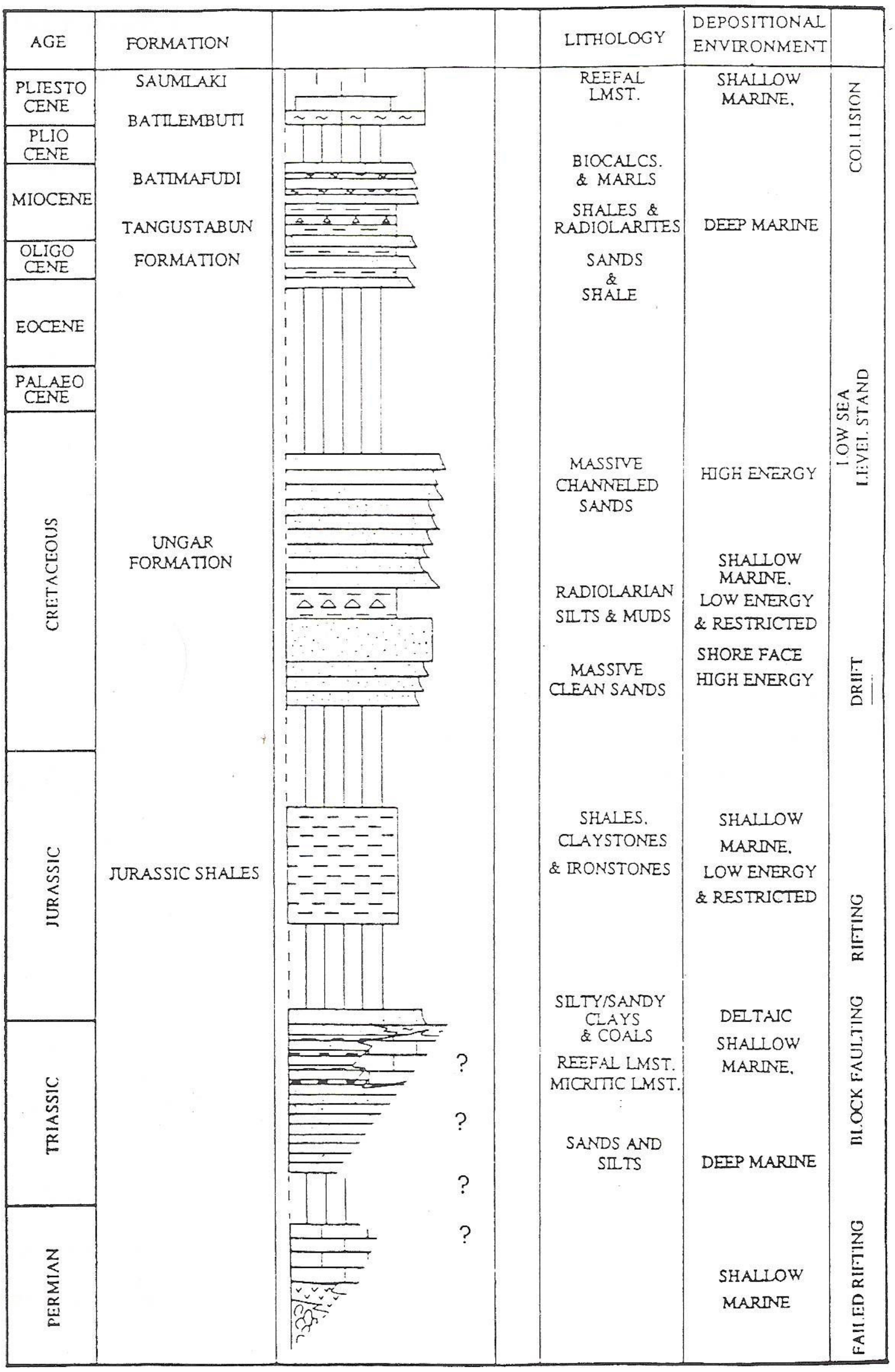


FIGURE 2.1.3.1 Stratigraphy of the Tanimbar Islands

EARLY TO MIDDLE JURASSIC - medium to dark grey shales which provide the matrix for the mud volcanoes. Carried to the surface by the shale are ferro-manganiferrous nodules, baryte, pyrite, calcite and belemnites including ~~Belemnopsis~~ of Middle to Late Jurassic age. The following ammonites were collected by the author and identified by Prof.D.T.Donovan(University College,London):

~~Schlotheima~~ (Hettangian)
~~Agassiceras~~ (early Sinemurian)
'Astheroceritid' (late Sinemurian)
~~Glevicerus~~ (late Sinemurian)
~~Tragophylloceras~~ (Pliensbachian)
~~Dactylioceras~~ (early Toarcian)

Other poorly preserved ammonites are Upper Toarcian or simply 'Liassic' in age. A number of nautiloids are provisionally identified as ~~Cenoceras~~, typical of the Lower Jurassic. A set of Ichthyosaur jaw bones, complete with teeth, was also found at a mud volcano by H.Sugilar(GRDC). Palynological evidence indicates an Early to Middle Jurassic (Pliensbachian to Callovian) age for mud collected from the matrix of a mud volcano. The shale was probably deposited in a low energy environment which was in part anoxic. Preliminary palynological determinations suggest a shallow, inner shelf environment, comparable to the Lias of Northwest Europe. Stratigraphic thicknesses are unknown but are probably 100s of metres.

CRETACEOUS AND/OR EARLY PALEOGENE - the Ungar Formation is a new stratigraphic division proposed by Charlton(1988). The unit is found on Ungar Island, and a number of other islands within the Selat Jamdena region, while rocks of similar lithology are commonly found as clasts in mud volcanoes. Two sub-units are recognised. First is a coarse (3-4mm) mature quartz-sandstone, pink or orange in colour with poorly defined bedding and massive in structure, which was probably deposited in a fluvial/deltaic environment. The second is a greenish or buff, fine to medium grained, arkosic sandstone with a glauconite and clay matrix, probably deposited near a delta. Both types are unfossiliferous. For the formation as a whole Charlton(1988) estimates a thickness of at least 1000m.

PALAEOGENE TO EARLY MIOCENE - the Tangustubun Formation consists of radiolarian cherts interbedded with thin non-calcareous siltstones, infrequent turbidite sandstones and shale horizons. The sandstone-shale sequences fine upwards suggesting a distal turbidite origin, sourced from the Australian Shelf. Thickness of the unit is unknown but is probably less than the 600m estimate of Sukardi and Sutrisno(1981). Quartz sandstones make up 50 - 90% of the thickness and shales 10 - 50%.

OLIGO-MIOCENE - a number of samples from mud volcanoes have been dated to within this age range. All are shallow water to non-marine sediments and include well-sorted arenaceous sandstones with benthic forams and sandstones with chert clasts. An immature deltaic marl has been dated as possibly Miocene in age.

MIOCENE - the Batimafudi Formation comprises white marls with intercalations of calcarenite turbidites. Sukardi and Sutrisno(1981) report that the proportion of marl to calcarenite increases westwards across Yamdena and this led them to create the Marl Member, Batimafudi Formation, for western Yamdena. However, Charlton(1988) states that this marl/calcarenite compositional differentiation is not confirmed and that there is considerable lateral variation in relative composition across Yamdena. Ages for the formation based on foram identification range from Early to Late Miocene (de Smet,1986 and 1988). De Smet(1988) has determined that the Batimafudi is a sequence of slope deposits, the sediments probably being derived from Palaeogene and Early Miocene rocks. Thickness is estimated to be 700 - 1000m.

PLIO-PLEISTOCENE - the Batilembutu Formation is dated as Plio-Pleistocene by Sukardi and Sutrisno(1981) and consists of marls with a foraminiferal limestone in the upper part. However, de Smet(in Charlton,1988) reports a Pleistocene age for the formation and states that no rocks of Pliocene age have yet been found in the Tanimbar Islands. The unit was deposited in a shallow water shelf location and shows a shallowing upwards into reef limestones. Thicknesses vary considerably due to the draping nature of the formation over previously thrusted Miocene and older units.

PLEISTOCENE (??) - during the 1986 and 1987 field seasons a marked unconformity was noted in several river sections between deformed Miocene rocks of the Batimafudi Formation and an undeformed clay rich in marine molluscs. The unconformity surface is planar and cuts across earlier structures, and is thought to represent a former peneplain that has now been uplifted and tilted a few degrees to form the gentle topographic slope down to the western coast of Yamdena.

QUATERNARY - raised coral reefs of the Saumlaki Formation are widely distributed around the coast of the Tanimbar islands. There are also outcrops some 8km inland at an elevation of approximately 150m, in southern Yamdena. In most areas reef elevations do not exceed 50m. Areas without raised reef may have undergone recent coastal subsidence or, conversely, rapid uplift coupled with excessive sediment deposition inhibiting reef growth. The latter case may apply to parts of the Selat Yamdena region.

2.1.4 NON-STRATIGRAPHIC UNITS IN THE TANIMBAR ISLANDS

Sukardi and Sutrisno(1981) classified all non-stratigraphic units as belonging in the Molu Complex. However, Charlton(1988) claims that part of the Molu Complex is a stratigraphic unit - the Ungar Formation (previous section) and suggests that the remainder of the Molu Complex, and part of what Sukardi and Sutrisno(1981) referred to as the Batilembuti Formation, should be subdivided into the Laibobar Metamorphic Complex and the Babuan Mud Complex.

2.1.4.1 The Laibobar Metamorphic Complex

The Laibobar Metamorphic Complex is found exposed on the 'inner islands' and occurs as clasts in mud volcanoes in the Selat Yamdena region. The complex comprises metasediments and igneous metabasites. Metasediments include marble, marmorised limestone, stylotized limestone and local occurrences of scaly clay. These metasediments have experienced low temperature-high pressure environments typical of a forearc and are probably metamorphosed equivalents of rock types exposed elsewhere in the island group. The metabasites include metagabbros, metadolerites and serpentinites. One of the metabasites has an amphibolite-calcic feldspar paragenesis indicative of medium to high amphibolite metamorphism, requiring a high temperature-pressure gradient.

2.1.4.2 The Bubuan Mud Complex

Charlton(1988) classifies the Bubuan Mud complex as a melange unit comprising blocks of various rock types in a clay matrix. Erosion can preferentially remove the clay leaving a lag deposit of mixed boulders. Many of the areas marked on the geological map(Sukardi and Sutrisno,1981) as Molu Complex are redesignated as eroded Bubuan Mud Complex. The matrix is medium to dark grey clay and has been dated as Early to Middle Jurassic (see section 2.1.3). The most common clasts are ferro-manganiferous nodules which are tentatively assigned to the Jurassic because of their similarity to rocks from the Wai Luli Formation of Timor. Baryte and pyrite also occur in small quantities. Triassic and possibly Cretaceous sandstones occur in variable amounts across the islands. Other rocks include calcilutite, Oligocene reef calcarenites, Tertiary limestones, serpentinites and metabasites.

2.1.5 GEOLOGY OF THE KAI ISLANDS

2.1.5.1 Introduction

The following account of the geology of the Kai Islands is based on the Preliminary Geologic Map of Achdan and Turkandi(1982) and reports by de Smet(1988), Charlton(1988), Kaye and Milsom(1988), Charlton, Barkham and de Smet(1989) and Kaye(1989).

2.1.5.2 Kai Besar

Kai Besar is the most easterly island of the Kai Group, lying at the western margin of the Aru Trough. It is approximately 10km wide, 75km long and has elevations approaching 800m.

The structure of the island is remarkably simple, consisting of a gently west-dipping sedimentary sequence cut by four major north-south normal faults with downthrows to the east. These normal faults are off-set by east-west wrench faults which displace sections of the island.

Kai Besar consists of rocks ranging in age from Middle Eocene to Quaternary. The oldest unit is the Yamtimur Formation, composed of grey calcareous shales, which pass up gradationally into the calcarenites of the Upper Eocene Elat Formation. These are overlain by the Middle-Upper Oligocene Tamangil Formation, which is a shallow water shelf carbonate. Overlying these are the reef and shelf carbonates of the Miocene Weduar Formation and Pliocene shelf carbonates of the Weryahan Formation. Quaternary reef occurs locally at the northern and southern tips of the island.

The stratigraphy is summarised in Figure 2.1.5.2.

STRATIGRAPHY OF KAI BESAR

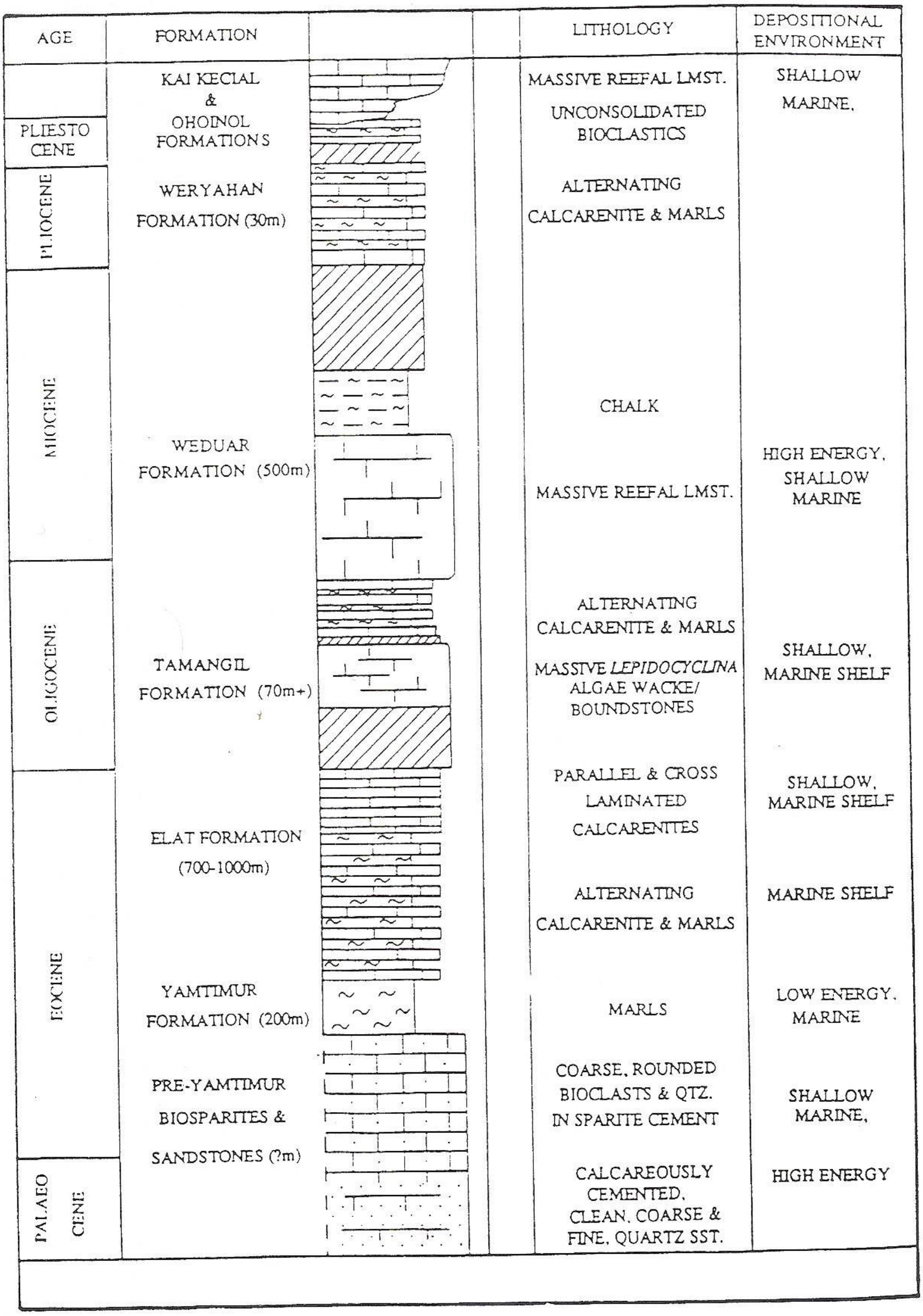


FIGURE 2.1.5.2 Stratigraphy of Kai Besar

2.1.5.3 Kai Kecil and the Western Kai Islands

Kai Kecil is separated from Kai Besar in the east by Selat Nerong. Kai Kecil is flat, with elevations uniformly reaching 100m in the centre of the island. The Tayandu Islands are a small group some 30km west of Kai Kecil.

The geology of Kai Kecil is dominated by raised reefs of the Pleistocene Kai Kecil Formation. This unit covers nearly all of the island and the surrounding islets. However, Kecil is dissected by NNW-SSE elongated topographic lows, some of which are inundated by the sea, within which marls and biocalcarenites of the Pleistocene Ohoinol Formation and Pliocene Weryahan Formation outcrop.

The Tayandu Group are mostly composed of reef limestone of the Kai Kecil Formation except for Tanjung Matot, on Tayandu Island, where a mud volcano is sited. The ejecta include ferro-manganiferous nodules, Triassic sandstones, Jurassic ironstones and a variety of younger carbonates and sandstones. The similarity of this ejecta to that from the Tanimbar Islands is striking and suggests that the crust under the two areas is similar.

The 'inner islands' are situated some 30km west of the Tayandu Group and border the Weber Deep. The islands are, from south to north, Fadol, Wonin, Manggu, Kur, Kaimeer, Tengai and Bui. Most of them are only 2-3sq. km. in area, the largest being Kur which is approximately 50sq.km.. The geology of these islands, except Kur and Fadol, is simple with only reef limestones of the Kai Kecil Formation exposed. The exceptions have coastal exposures of the ubiquitous Kai Kecil Formation surrounding outcrops of micaquartz-feldspathic gneiss, micaschists and hornblende schists. The nature of the contact between the overlying Kai Kecil Formation and the acid metamorphic rocks is not known. The metamorphics are interpreted by most workers as Australian crustal basement material.

CHAPTER 2.2

GRAVITY SURVEY OF THE TANIMBAR AND KAI ISLANDS

2.2.1 INTRODUCTION

This chapter describes the acquisition, processing and interpretation of gravity data obtained in the Kai and Tanimbar Island groups in eastern Indonesia between 3 September - 5 November, 1987, and 25 March - 6 May, 1989 (appendix B).

The primary aims of the geophysical surveys were to obtain sufficient gravity coverage for the islands to allow regional maps to be prepared at 1:500,000 scale, and to locate gravity stations in positions that would allow the later integration of land and marine geophysical data.

The 1987 geophysical fieldwork (appendix B) and the parallel geological investigations were carried out jointly by members of the University of London Consortium for Geological Research in SE Asia and officers of GRDC. The geological team consisted of T.R. Charlton (Geologist, University of London), H. Samodra (Geologist, GRDC) and H. Sugilar (Technical Assistant, GRDC). The geophysical team consisted of S.J. Kaye (Geophysicist, University of London), Sardjono (Geophysicist, GRDC) and Zainal Hayat (Assistant Geophysicist, GRDC).

In 1989 the geological team consisted of T.R.Charlton, S.Barkham and M.E.M. de Smet, all from the University of London. Geophysical fieldwork (appendix B) was carried out by the present author. Both teams were supported by Mr.J.J.Papilaya from Pertamina, the Indonesian state oil company.

2.2.2 GRAVITY SURVEY

2.2.2.1 The surveys

The first gravity survey in the Tanimbar and Kai Islands, was conducted by the University of London and the Geological Research and Development Centre(GRDC) in 1987 (Kaye and Milsom, 1988) and sponsored by Union Texas (SEA) and Idemitsu Oil Development Company (Fig 2.2.2.1.1 and appendices C & D).

The 1989 combined geological and geophysical survey was again funded by Union Texas (SEA) and the Idemitsu Oil Development Company, and designed to increase coverage of the island groups (Fig 2.2.2.1.2 and appendices E & F).

2.2.2.2 Survey Ties

The 1987 and 1989 surveys used the Indonesian Network base station at Pattimura Airport, Ambon, established in the early months of 1987 by officers of GRDC (see Appendix G: gravity base stations). The 1987 and 1989 surveys are additionaly tied to a number of field and sub-base stations throughout the Tanimbar and Kai Islands. Analysis of these datasets indicate that on average the 1989 observed gravity values exceed the 1987 by 0.06mGal. The 1989 data in Appendix E & F have been decreased by this amount.

2.2.2.3 Data collection, tidal corrections and station positioning

For both surveys gravity readings were taken using a LaCoste-Romberg Model "G" gravity meter, the small inherent drift allowing loops to be extended for periods of days before being closed by a repeat reading at the base. Because of these long loops, tidal corrections had to be applied and drift corrections had to be made with more care than is general in regional surveys.

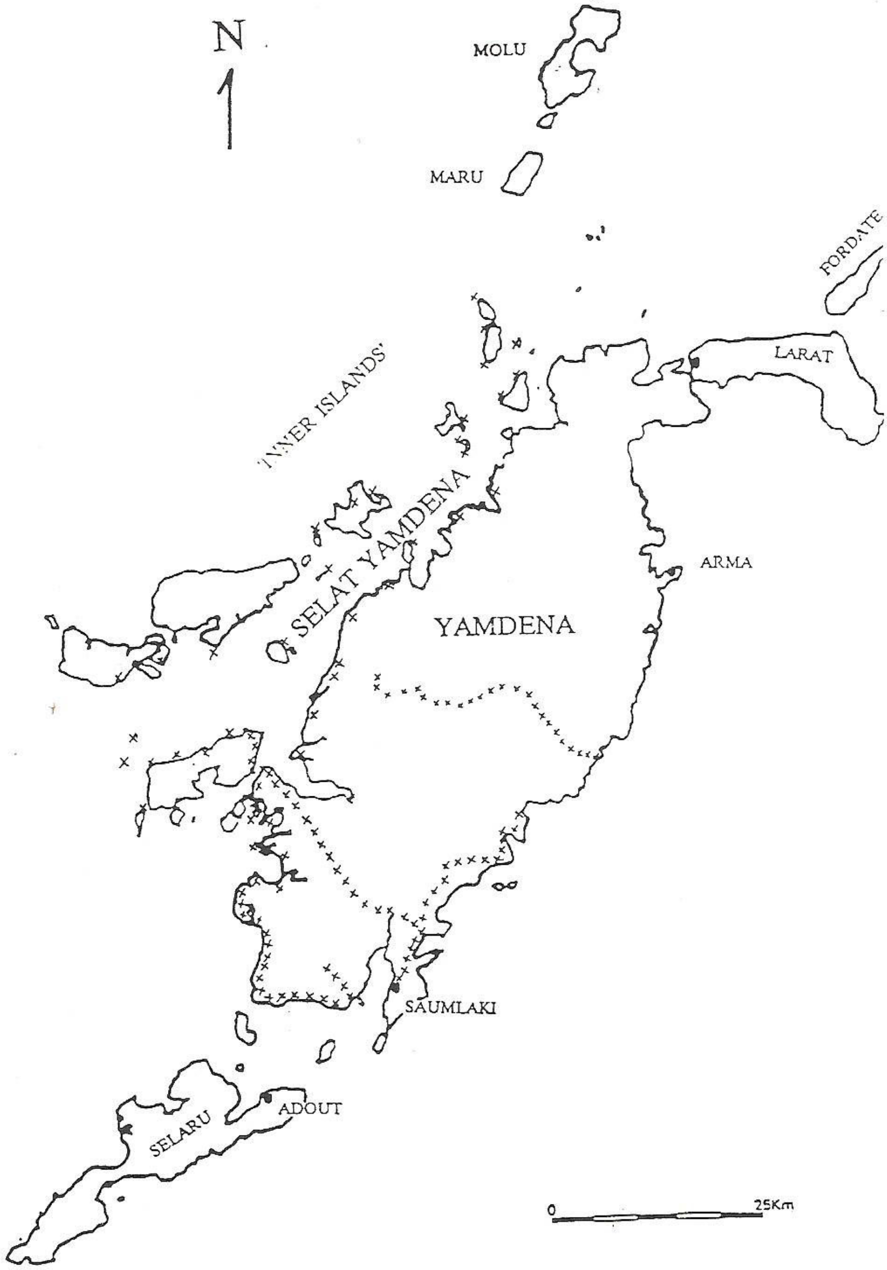


FIGURE 2.2.2.1.1 Gravity station location map of the 1987 University of London/Geological Research and Development Centre, Bandung, survey of the Tanimbar Islands

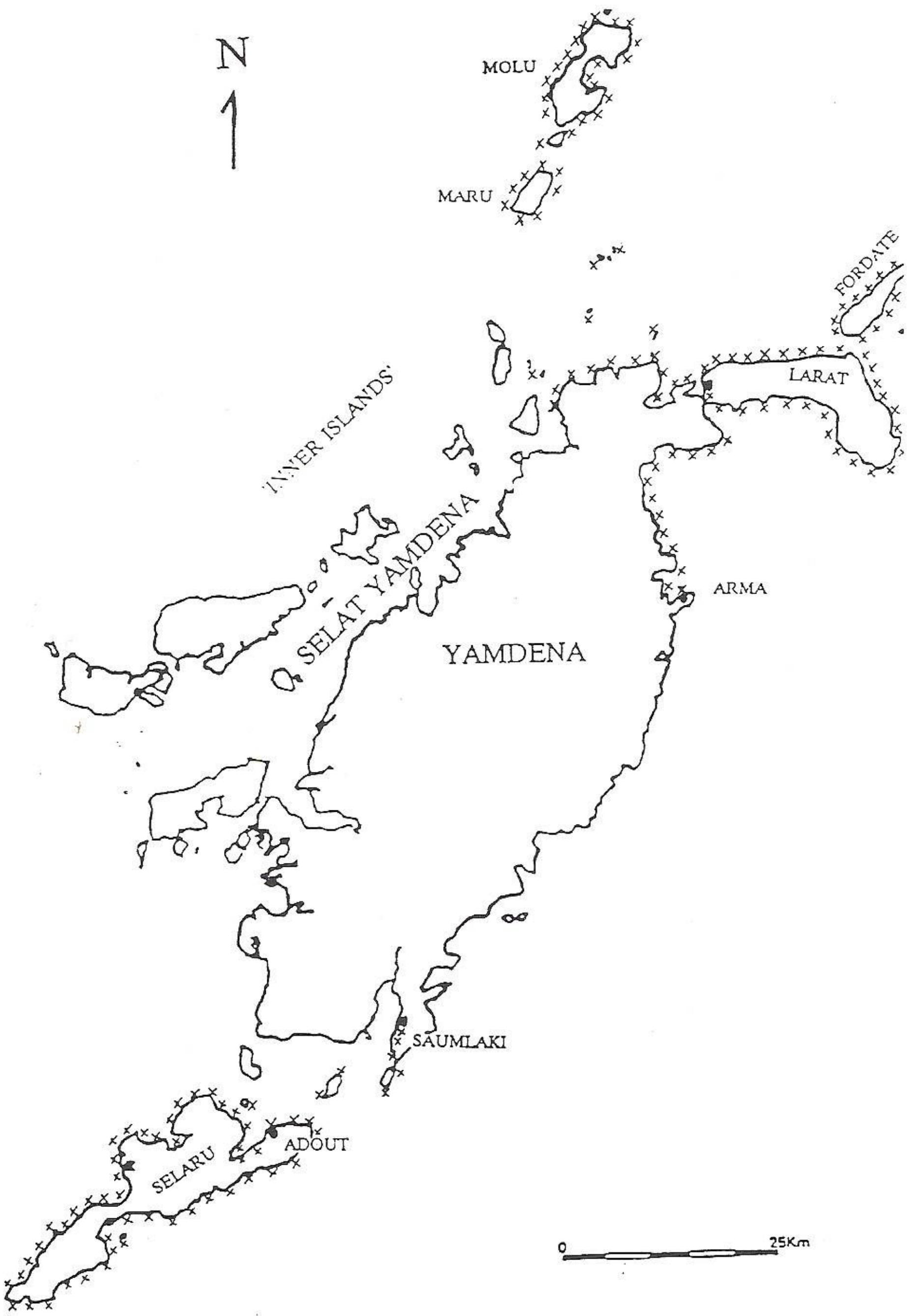


FIGURE 2.2.2.1.2 Gravity station location map of the 1989 University of London/ P.T.Corelab survey of the Tanimbar Islands

Tidal corrections were made utilising a program based on an algorithm published by

Longman (1959). A linear drift rate was assumed and corrections were made to 0.001mGal, giving a final accuracy of 0.01mGal. The drift-corrected meter values were then converted to absolute 'observed gravities'.

Gravity stations located on the coast were plotted in the field directly on 1:250,000 scale maps, the only maps available. These proved to be accurate in their delineation of coastal features, enabling coastal stations to be positioned to within 125m (the size of any mark made on the map). On returning to London the islands and stations were digitised using a Universal Transverse Mercator (UTM) grid, resulting in stations positioned with a false accuracy of less than one metre. This level of precision has been retained in the listings in Appendices C,D,E, & F. The initial field-plotted accuracy of 125m (0.5mm on a 1:250,000 map) corresponds to a theoretical latitudinal gravity change of 0.02mGal.

The 1987 inland traverses were positioned on the maps using compass bearings and paced or tachometer distances, and were then digitised. In deriving absolute positions from the field data, it was found necessary to amend the field logged distances and alter bearings by small amounts to close traverses at known locations. For example, distances along the 60+ km. foot traverse across Jamdena conducted in 1987, from Lurumbun on the east coast to Makatian on the west, were corrected using a factor of 1.0625 (i.e. an approximate increase of 6m in every 100m logged) and a bearing correction of 2.1 degrees. The theoretical relative accuracy for station positioning of about 7m is retained in the data listings, which thus assume linear errors in distances logged and systematic errors in bearing. Since the errors will in reality be neither linear nor systematic, and since each inland traverse is tied to coastal points which may themselves be in error by some 125m, the actual error in positioning each inland station must be close to 200m. This 200m error is equivalent to less than 1mm on the 1:250,000 map, and corresponds to a theoretical latitudinal gravity change of approximately 0.03mGal, an amount too small to be significant.

2.2.2.4 Elevations

For the 1987 and 1989 surveys the elevations of coastal stations were estimated by direct reference to sea level, with an accuracy of about 0.5m in the worst cases when the sea was rough and there was a heavy surf. Most station heights are known more accurately than this. Corrections for the state of the tide have not yet been made to the 1987 data, so there is an additional uncertainty of about +/-1m in the heights presented in this study. The average probable error of about 1m corresponds to an error in Bouguer anomaly of 0.2mGal. The 1989 data have been corrected for the state of the tide.

All stations in the 1989 survey were on the coast and consequently have the smallest errors due to elevation inaccuracies. However, the 1987 survey includes numerous inland stations, elevations being measured barometrically and hence giving rise to errors of 1 to 3mGal in Bouguer anomaly.

During 1987, elevations calculated at inland stations have larger errors because of the inherent lack of precision in the use of altimeters, exacerbated by the logistical problems that ruled out the use of a base altimeter on a day-to-day basis. The best that could be done was to plot a standard pressure-dependent graph of elevation against time for the daylight hours, based on periods of extended observation at the survey bases and at various coastal stations. Pressure-corrected elevation values for inland stations were derived from this graph. This method assumes that there is little variation in the diurnal barometric pressure curve from day to day and also that pressure changes at the coast are the same as the changes inland. Fortunately, the first assumption is generally valid in tropical areas and the method has produced elevations that are for most stations in agreement with heights on the 1:250,000 maps.

Marked differences exist between map and derived elevations for stations at high elevations along the east coast of Jamdena, where the derived elevations always exceed the map elevations. There are three possible reasons. Firstly, the pressure-dependent time/elevation graph may be inaccurate at elevations above about 100m. Secondly, the anomalous values may be due to localised pressure cells created by the on-shore winds along the coast. Thirdly, the 1:250,000 scale maps may be in error; certainly the topography is more rugged than the maps suggest. None of these possible causes can be confirmed or quantified and consequently the graphically derived values have not been amended.

A possible error range for elevations can be estimated only by applying the graphical method to known station heights, and, since these are all at sea-level, the sample is a very biased one. Various attempts were made to define the error mathematically but none proved sufficiently precise. There is an error range of 10 - 15m for stations read between 15.00hr and 18.00hr but for other times during the day the error range is 5.0m. Therefore, disregarding any possible unquantifiable errors, the error in elevation for inland stations between 07.00hr and 15.00hr is estimated to be 5m, which corresponds to 1.0mGal of Bouguer anomaly. Elevations for stations read between 15.00hr and 18.00hr could be in error by 15m (3mGal Bouguer anomaly), but relatively few stations were read during this period, and of those the majority are not at high elevations and have been constrained by the 1:250,000 scale map.

2.2.2.5 Gravity reductions

The latitude correction was made by subtracting the 'normal' gravity calculated from the 1967 International Gravity Formula (below) from the absolute 'observed' gravity.

$$g(\text{normal})=978031.85(1+0.005278895\ \text{Sin}^2\ L + 0.000023462\ \text{Sin}^2\ 2L)$$

(where L = latitude of the station)

The free-air correction was made using the correction factor of 0.3086mGal/m. Application of the free-air and latitude corrections gives the free-air anomaly.

A two-stage approach was used to calculate Bouguer anomalies. In the first stage the topography was represented by a flat Bouguer plate of density 2.67g/cc and a thickness equal to the elevation, h, of the station above sea level, giving:-

$$b= 2\ \text{pGh}\ \ (= 0.1119\text{mGal/m})$$

As a second stage, local terrain corrections were made for the topography within 200m of the stations using a nomogram based on Hammer charts. Allowance was made for topographic masses above the Bouguer plate and pseudo-masses infilling valleys due to the over-correction of the plate. The results were then plotted and contoured.

The gravity listings in appendices C,D,E and F include the following:-

Station number, day, hour, minute, meter reading, tide correction value, tide corrected meter reading, drift corrected meter reading, elevation, latitude, longitude, observed gravity, normal gravity, terrain correction, free-air anomaly and Bouguer anomaly values at 2.10, 2.30, 2.50 and 2.67 g/cc density.

2.2.3 GRAVITY FIELD OF THE TANIMBAR ISLANDS

The Bouguer anomaly map (Fig.2.2.3.1) shows that station distribution across the island group is sufficient to allow contouring at a 5mGal interval. This interval is considered reasonable taking into account the magnitude of the possible position errors and, more importantly, the maximum probable error of 3mGal in the Bouguer anomaly values due to elevation inaccuracies at some of the inland stations.

2.2.3.1 Bouguer Anomaly Features

The island of Selaru, to the south-west of Jamdena, is the second largest in the Tanimbar Group and elongated NE-SW, thereby following the trend of the Tanimbar Trough as it turns progressively northward in this region. Geological strike and Bouguer anomaly contours are also aligned NE-SW, with anomaly values increasing from -30 to -25mGal on the NW long-side of the island, to -5 to 0mGal on the opposite SW coast where the steepest gradients are found. The almost even distribution of this anomaly pattern along the NE-SW long axis of the island suggests that it is possibly caused by a geological feature that is at least as long, but broader, than the island. Seismic images in the area show large antiformal structures sub-parallel to the Tanimbar Trough. Selaru is possibly underlain by a large asymmetric antiformal structure, with the steepest limb situated between the island and the trough. The wavelength of the Bouguer anomaly field indicates a 15 to 20km width to the antiform and a depth which would place it within the under-plating zone of the forearc complex.

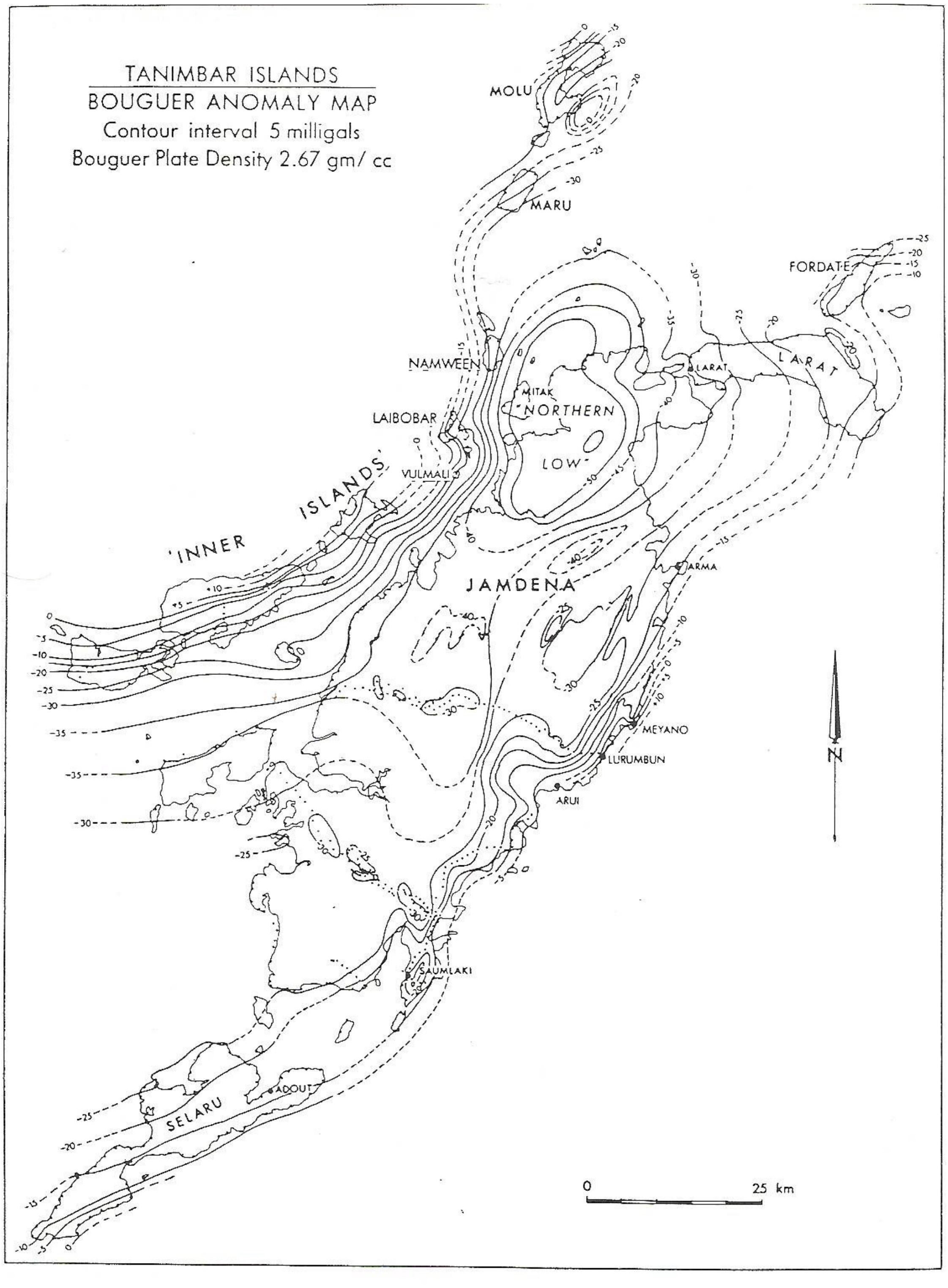


FIGURE 2.2.3.1 Tanimbar Islands Bouguer anomaly map

On a more local scale, there is an indication of normal faulting, or small scale strike-slip faulting with a normal component, parallel to the NE-SW long axis of the island. The best example occurs in the bay to the west of Adout, where Bouguer anomaly values increase by 3.5mGal in a NW-SE direction across the bay.

In the vicinity of Saumlaki the Bouguer anomaly contours turn northward through 45° to run parallel to the east coast of Jamdena. It is possible that the area between Selaru and Jamdena has a number of NNE-SSW striking wrench zones which pass from the region of the 'inner islands' across Jamdena. Their existence is suggested by the presence of mud-volcanoes, deep NNE-SSW elongated embayments, high elevated reef escarpments, steep elongated NNE-SSW margins to coral platforms and off-sets in the Bouguer anomaly field. A wrench zone may exist in the bay on the east side of which Saumlaki is situated.

The total range in Bouguer anomaly along the east coast from Saumlaki to Arma is about 30mGal, from -25 to +5mGal. The gradients are steep, amounting to approximately 10mGal/km near Lurumbun and Meyano, with contours trending sub-parallel to the coast. Bouguer anomaly gradients are steeper suggesting a greater degree of thrusting and imbrication and/or a steeper set of limbs to the antiforms in this region. Also, this coastal region has a moderately high and rugged terrain, dissected by constantly rejuvenated rivers, which suggests rapid differential uplift, possibly caused by a progressively developing antiforms within the underplated zone. It is also possible that the uplift and the eastwardly positive Bouguer anomaly gradient is in part caused by differential uplift of crustal blocks along strike-slip faults.

Although, the cause of this positive anomaly gradient is not evident in the exposed geology, dense masses must presumably lie close to the surface. Previous compilations of (largely marine) gravity data in the region have indicated less steep gradients and Bouguer anomaly values generally less than zero on the northern side of the Tanimbar Trough (c.f. Bowin et al,1980). The present surveys have indicated that the gradient immediately off Tanimbar is steeper than previously thought, although it may, of course, flatten a little way further out to sea.

Near Arui there is a westward embayment in the anomaly contours indicating a significant landward off-set in the east coast positive anomaly trend. To the north of this embayment the imbricated ridges of the accretion complex are clearly evident on the Landsat image of the island, while to the south imbrication is less evident resulting in a decrease in the lineation of the topography and a lessening in the sub-parallel alignment of Bouguer anomaly contours to the coast. Additionally, the +5 and 0mGal contours, which form part of the steep on-shore gradient to the north of the off-set, do not occur in the south where the anomaly gradient decreases to 3-5mGal/km. The off-set may have been created by a dextral WNW-ESE antithetic strike-slip fault.

In the central and southern regions of Jamdena, from the western margins of the elevated east coast ridges to Selat Jamdena, Bouguer anomaly values are typically in the range -30 to -35mGal and lack steep gradients. The markedly different character of the anomaly field, as compared to regions to the east, is reflected in the flat, flood-plain topography and a change in the exposed geology from mainly imbricated Miocene rocks in the east to the Bubuan Mud Complex, which covers large areas of mid and southern Jamdena. The boundary between these areas is generally sharp, with steep Bouguer anomaly gradients, indicating structural discontinuities which may be NNE-SSW striking wrench zones.

The northern third of Jamdena is dominated by a large Bouguer anomaly low (the Northern Low) which must indicate the presence of a large mass of low density material. The -50mGal contour encompasses a large area including the 'inner island' of Mitak and part of the northern reaches of Selat Jamdena. The Northern Low has a slight north-south elongation, with moderately steep gradients on the western margin situated over the 'inner islands'. The eastward positive gradients of the opposite margin decrease towards the east coast of Jamdena. The difference in gradient steepness on either side of the Northern Low is due to sharp differences in density contrast at the borders of the low. On the western border are the low to medium grade, Mesozoic metamorphics of the 'inner islands', while to the east are Tertiary, low density, imbricates. The low may be caused by thick sequences of Tertiary imbricates but this can not be confirmed.

Along the north-east coast of Jamdena, from Arma to Larat, the -10 to -35mGal contours from the mid-Jamdena region turn in a northerly, anti-clockwise direction around the Northern Low. This curving trend is broken on the eastern tip of Larat Island where the -10 and -15mGal contours have a NNE-SSW direction possibly associated with N-S structural lineaments which can be seen on the Landsat image. These lineaments are mirrored in the step-like form of the coast.

Fordate Island also escapes the influence of the Northern Low, having a northward negative gradient with Bouguer anomaly contours of -10 to -25mGal trending sub-parallel to the long axis of the island. Fordate is long, thin, high (max. elev. 259m) and comprised largely of Miocene rocks. The highest elevation occurs in the centre of the island. All gravity stations are situated on the coast near to sea-level and full terrain corrections have not been carried out. If these corrections were applied all Bouguer anomaly values would increase and those stations nearest to the centre of the island would gain the most, resulting in a sharply increased anomaly gradient with a positive trend to the SE. The gradient, contour direction and values would be similar to those seen between Arma and Arui on the east coast of Jamdena. It is possible that Fordate is a northerly continuation of the structures on the east coast with the greater elevation, the sharp drop to deep water, the anomalous topographic character and allignment of the island being due to NE-SW orientated thrusts, possibly bordered to the north and south by normal or stike-slip faults. Greater understanding of this area will be gained after examination of the marine data collected in 1989.

Elsewhere in the north the presence of faults is indicated by deep water channels, for example between Larat and Jamdena, and embayments in the northern Jamdena coast west of Larat. The influence of these faults is seen in the Bouguer anomaly contours which kink in the vicinity of Larat Town. Also, while surveying in this area the gravity meter on a number of occasions could not be nulled due to quarter or half scale deflections, indicating that there is micro-seismicity in the area. Indeed, local inhabitants report that on a number of occasions each year they are woken at night by small scale tremors.

Bouguer anomaly values increase from east to west across the 'inner islands' over the range -35 to +10mGal, with contours broadly conforming to the crescent shape of the island chain. North-west of the 'inner islands', oceanic crustal material underlies the Weber Deep, producing maximum Bouguer anomaly values of +250mGal. Previous Bouguer anomaly maps (eg. Bowin et al,1980) show values decreasing towards the Tanimbar Islands, reaching 0mGal adjacent to the 'inner islands'. The 'inner islands' may possibly be the site of contact between oceanic crust and Australian continental material of Mesozoic age, with the islands being overthrust out-of-sequence, onto the younger Tertiary forearc wedge of Jamdena.

The northern 'inner island' of Molu consists of Triassic sandstone and limestone and sandstones of the Early? Cretaceous Ungar Formation. Bouguer anomaly contours of -20 to 0mGal trend NE-SW across the island, with a steep positive gradient to the north-west - typical of the group. There is a localised Bouguer anomaly high situated over the south-east peninsular where dense Triassic limestones outcrop. The Landsat image shows a N-S lineament on the western side of the outcrop which can be traced to the north coast of the island. The anomaly gradient across this feature is 10mGal/km.

Between Molu and Maru Bouguer anomaly contours are markedly displaced to the south creating a sinuosity which is common through much of the 'inner islands' and indicative of structural displacement due to thrusts and wrench faults. The trend of contours on Maru and Molu are similar but south of Maru they turn south through approximately $45^{o,}$ becoming aligned NNE-SSW to the west of Mitak and the Northern Low. Here anomaly gradients are steep (5 to 8mGal/km) in an area where the ' inner islands' come closest to Jamdena. Contour sinuosity is pronounced and is probably due to thrust and wrench activity juxtaposing material of high and low densities, creating sharp density contrasts.

In the south the 'inner islands' diverge from Jamdena in a NE-SW direction, with Bouguer anomaly contours following the trend and increasing in value on the north-west side of the islands to +10mGal. Sinuosity is still present but less pronounced. Rock outcrops encountered here are similar to those in the north with Triassic sandstones and limestones and large areas of Ungar Formation sandstone, together with Permian limestone and volcaniclastics.

Southern Selat Jamdena is the site of a -35mGal low, the axis of which is situated in the middle of the strait. This contrasts with the axis of the Northern Low which is situated on-shore Jamdena. The southern low may be due to the presence of recently deposited low density detritus from Jamdena and the 'inner islands', while the Northern Low may be associated with thick Tertiary imbricates.

Selat Jamdena is possibly the site of numerous en-echelon thrusts and corresponding wrench faults which separate the largely Mesozoic 'inner islands' from the Tertiary rocks of Jamdena (see Fig.2.2.5.1). Mud volcanic activity is common throughout the straits and is probably related to the structural activity of the region. The large amounts of low density mud at the surface, together with that which must be entrained within thrust and wrench zones, contributes to the low Bouguer anomaly values measured in the straits area and across much of mid-Jamdena.

2.2.3.2 Cross-section modelling, Tanimbar

The cross-section used in the gravity modelling in the Tanimbars (profile Fig. 2.1.1.1) is based on the geological cross-section drawn by T.R.Charlton (1988, page 43). This shows zones of frontal accretion and underplating, the concepts being derived from studies of subduction-accretion processes. The Tanimbar Trough is assumed to have been a 'normal' subduction trench system, with oceanic crust subducting beneath a forearc complex, prior to the collision with the Australian continental margin. The Snellius 'geohistory curves' indicate that this collision took place in the Pliocene (de Smet, et al, 1989). Subduction is thought to have now ceased, as evidenced by the undisturbed Pliocene-Recent sediments seen draped over the imbricated units on seismic reflection profiles (Schluter and Fritsch 1985), and by the lack of strong deformation in the Pliocene-Recent rocks on Jamdena.

In the early stages of continental subduction part of the thick cover of Australian sediments would have been scraped off the downgoing slab to form the accretionary complex. Such complexes are thought to have dynamic stability which can be modelled in terms of a critical balance between the basal shear strength and the weight of the prism overlying the basal decollement. Thickening of the prism vertically beyond a critical size following horizontal compression will cause the weight of the prism to exceed the basal shear strength, causing lateral spreading and associated thrusting from the basal decollement. This then reduces the thickness of the prism, decreasing the weight of material above the decollement to an amount that can be supported by the shear strength of the rocks. The result is a dynamically stable triangular cross-section which is usually described as the critical taper model (Davis et al. 1983).

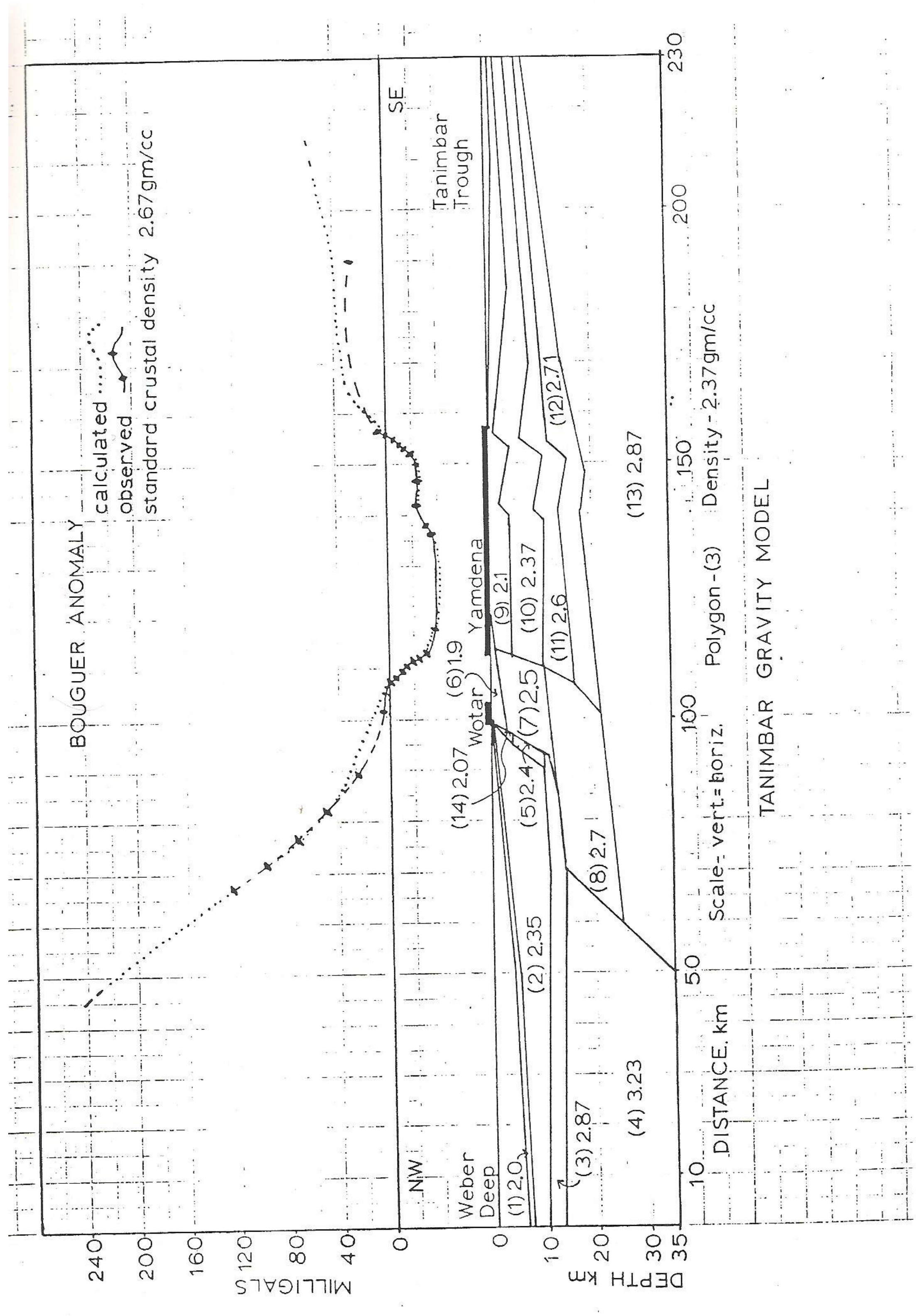


FIGURE 2.2.3.3.1 Tanimbar gravity model

Frontal accretion takes place when new thrusts propagate from the basal decollement into the overlying, previously upthrust sequence and terminate outboard of the previous thrust, thereby creating a new thrust slice at the front of the accreting imbricate stack. Other thrusts can propagate from the basal decollement but rejoin it at a higher structural level. This creates a thrust-bound package of sediments which accrete to the base of the imbricate stack. An accretionary complex can be divided into an upper level where frontal accretion is dominant (Polygon 9, Fig.2.2.3.3.1) and a deeper level of underplating (Polygon 10, Fig 2.2.3.3.1). Those parts of Polygons 9 and 10 SE of the accretionary toe, situated at the deepest part of the trough, have not been incorporated into the wedge. The basal decollement starts at the accretionary toe and descends under the Tanimbar Islands through Polygon 10 before terminating within the compressive/suture zone (Polygon 7, Fig 2.2.3.3.1). It is thought that the basal decollement under Jamdena lies within the Lower to Middle Jurassic shales of the Australian margin. Large amounts of ironstone and shale of this age are brought to the surface by mud volcanoes in the Selat Jamdena area, and the shales have an appropriate shear strength and are close to the right structural level within the subducting sequence to allow decollement formation. The basal decollement may also step down into the deeper levels of the Australian sedimentary cover under western Jamdena and the 'inner islands'. A secondary, higher level, decollement is thought to exist within the shales of the Early Miocene Tangustubun Formation.

The boundary between Polygons 9 and 10 has been used in the gravity model to account, in part, for the steps in the anomaly field over the eastern half of Jamdena. The first step, from +5 mGal to -25 mGal, occurs over the eastern ridge complex which is thought to be due to overthrusting and/or antiformal folding of underplated and imbricated material. The second step in the anomaly field, further towards the centre of Jamdena, is explained in a similar fashion. Each anomaly step marks the western edge of internally thrusted and folded imbricate packages. The first package is bounded by a strike-slip fault along which Jamdena has been displaced in a north-westerly direction as a result of the continuing oblique convergence of the Australian craton upon the Tanimbar forearc. The second step marks the eastern side of the main Jamdena wrench zone which cuts in a NNE-SSW direction across Jamdena from the 'inner islands' to Saumlaki (Fig. 2.2.5.1). Here, over central and western Jamdena, to within 5km of Selat Jamdena, Bouguer anomaly values are almost constant at 35mGal. It should be noted that the anomaly as modelled does not entirely explain the observed field. This is because exclusively near-surface polygons were not used and extreme simplicity was maintained, as is appropriate in a region which has been geologically mapped only at reconnaissance level and where seismic data are lacking.

Permo-Triassic sediments and continental basement rocks (Polygons 11 and 12 respectively) lie below the basal decollement and were probably not imbricated during subduction. It is thought likely that when subduction ceased, these deeper units were involved in overthrusting from the collision zone into the underplated zone (Polygon 10) as a result of the continuing convergence of the Australian craton. Further convergence has led to NW-SE displacement of Jamdena along numerous strike-slip faults which can be followed at depth by the steps in the surfaces of the underplated and Permo-Triassic zones beneath eastern and central Jamdena.

The transition beneath the Australian sedimentary sequence to densities typical of the lower crust is marked by the upper surface of Polygon 13, which descends to 35km, the final model depth. This implies that the continental crust under the region modelled is everywhere thicker than 35km and that the Moho is flat. Additional modelling was conducted to determine the gravity effect of increasing the Moho depth from 35km under the Australian shelf to various depths under Jamdena. With a maximum Moho depth of 40km the gravity effect of rock below 35km was a maximum of -12mGal in the middle of Jamdena. Similarly, at a Moho depth of 45km the result was -35mGal. Of course, the configuration and density of material at these depths is not known. Consequently, the gravity effect of this material on the long wavelength components of the gravity field can not be verified.

Schluter and Fritsch (1985) produced the 'BGR' model where the average thickness of the continental crust is only 25 to 30 km. However, their model relates to an area to the north of Tanimbar in a region probably tectonostratigraphically very different (profile Fig. 2.1.1.1). This difference is in part due to a possible decrease in the thickness of Australian units in the BGR area, but more importantly to the different tectonic regimes. The BGR model line is orientated WNW to ESE and lies to the north of Tanimbar, and is sited over the southern margin of a bathymetric trough (Fig.2.1.1.1). This trough links the margins of the Weber Deep, in the NNW, to the junction between the 1500m deep Tanimbar Trough and the 3500m Aru Trough, in the SSE, marking the north-eastern boundary of the Tanimbar Islands block. Schluter and Fritsch (1985) regard it as a major wrench fault system, presumably accommodating differential movement between Tanimbar and Kai, but there seems to be no evidence for it extending across the Aru-Tanimbar system to the continental shelf in the Arafura Sea.

TABLE 2.2.3.1

Polygon Number	Density(g/cc)	Description
1	2.0	Surface sediments of the Weber margins
2	2.35	Consolidated sediments of the Weber margins and oceanic crustal material
3	2.87	Oceanic layer 3 of the Weber margins
4	3.23	Mantle material of the Weber margins
5	2.4	Obducting oceanic layer 3
6	1.9	Mud volcano zone
7	2.57	Thrusted Mesozoic and Pre-Mesozoic Australian craton rocks
8	2.7	Deeper level impact zone of the Australian craton
9	2.1	Frontal accretion zone
10	2.37	Underplating zone
11	2.6	Australian Permian-Triassic rocks
12	2.71	Australian sedimentary basement
13	2.87	Australian lower crust
14	2.07	Upper level of obducting oceanic layer 3

The steep Bouguer anomaly gradient over the margins of the Weber Deep marks the contact of oceanic mantle (Polygon 4) and Australian continental material (Polygons 8 and 13); the best 'calculated' slope being generated by a 45 degree contact below about 15km. Polygons 1,2 and 3 are believed to provide a reasonably accurate representation of the upper oceanic crust, and it therefore follows that the collision suture at depth is presently located some 35km north-west of the Tanimbars.

Oceanic layer 3 (Polygon 3), density 2.87g/cc, has been continued and thinned in the model towards the Tanimbars. The geological evidence for this 'obducted' layer 3, represented by Polygons 5 and 14, is the presence of metabasics on the island of Laibobar, and of serpentinites and very altered basic rocks brought to the surface by mud volcanoes. The hydration and alteration of these basic rocks is modelled by the decrease in density of Polygons 3, 5 and 14. The geophysical evidence is the regional magnetic field which, according to Bowin et al (1980), is disturbed from the Weber Basin to the 'inner islands', indicating oceanic crust close to the surface. SE of these islands the magnetic field is less disturbed, suggesting the presence of continental crust. Continuation of the lower-most sections of the oceanic crust towards the 'inner islands' can account for these geological and geophysical data. However, it is possible that these same data could be explained by overthrusting of the former Australian oceanic material caught up in the collision zone.

Between the 'inner islands' and the NW coast of Selat Jamdena is an area of mud volcanism and, supposedly related, shale diapirism (Polyon 6). This polygon also models the effect of large quantities of low-density sediment deposited into Selat Jamdena from the 'inner islands' and Jamdena. Many of the rocks brought to the surface by mud volcanoes, a mix of Weber oceanic and Australian Shelf sediments, are greenschist to amphibolite grade metamorphics which show the effects of the migration of metal-rich hydrothermal fluids. Temperatures and pressures were probably elevated beyond the depth norm in this thrust zone. The relationship between the elevated temperatures and hydrothermal fluid migration is not clear. The iron and manganese deposits that coat some sedimentary units probably derive their metal content from the oceanic sediments and from the iron-rich Lower Jurassic of the Australian shelf.

The 'mud volcano' Polygon 6 has been extended to the Jamdena coast to model the Bubuan Mud Complex deposits mapped in this region, although it is known that a number of other sedimentary units are present. Polygon 6 is closely related to Polygon 14, but has a greater percentage of the Lower Jurassic mud volcanic matrix and associated products. The parent sediments for the clasts of Triassic sandstones and Jurassic ironstones must have been transported down the subduction zone whilst it was still active. This would place them in the Permo-Triassic Polygon 11 and the underplated zone (Polygon 10) which, as modelled, descend to a mean depth of 13km beneath Jamdena. It is difficult to see how they could have been brought to the surface by diapirs sourced in the Jurassic shales unless there was also tectonic mixing. Gas moving up from depth may play an important part in the whole process.

The mud volcano zone is also fed with material from Polygon 7 at a density of 2.5g/cc. This polygon has been inserted to account for the steep positive gravity gradient in Selat Jamdena. Within this zone will be the oldest imbricated and underplated sediments of the Australian craton, together with Australian basement rocks. The density of 2.5g/cc has been chosen as appropriate for the older Australian sediments, in view of the depth to which they have been carried. It is reasonable to assume that some tectonism and associated metamorphism occurs within this zone as shown by outcrops in the 'inner islands'. The inclined eastern margin of

Polygon 7 terminates the imbricated and underplated zones (Polygons 9 and 10) near to the west coast of Jamdena. This margin represents a major out-of-sequence overthrust which has emplaced the older and denser Mesozoic and Pre-Mesozoic Australian rocks onto the younger and less dense Tertiary rocks of Jamdena. The 'inner islands', which largely consist of Mesozoic and Pre-Mesozoic rocks, are modelled by Polygon 7. Overthrusting within this region is probably more prevalent than the model implies, and this is shown on the simple structural map (Fig. 2.2.5.1).

Part of Polygon 7 underlies the leading edge of the obducting layer 3 (Polygon 3) and is envisaged as transitional to the deeper level collision zone of Australian sediments and basement (Polygon 8). This polygon is the leading edge of the Australian sediments which directly overlies the Australian lower crust and is in contact with the oceanic material at the Weber margins. The sediments were carried to this depth in the last stages of collision and are probably undergoing considerable pro-grade metamorphism and overthrusting. These overthrusts may be propagating rearwards of the subduction zone, through the lower crust, into the Australian sedimentary pile of Polygons 7 and 12, which in turn may cause compressional overthrusting of units in Polygon 11 (Australian Permian-Jurassic rocks). Overthrusting from these depths might be transmitted as far back on the Australian craton as the south-east coast of Jamdena and may have caused the present-day elevation of Jamdena. Present day uplift rates for Jamdena are about 13cm/ka (M.E.M.de Smet, pers. comm.).

2.2.4 GRAVITY FIELD OF THE KAI ISLANDS

The 1987 gravity survey by the University of London and GRDC used the extensive road network on Kai Kecil to cover most of the island, with additional stations placed on Tayandu and Kai Besar to provide information on the regional gravity field. The 1989 University of London/PT Corelab survey extended coverage across the Kai Islands region to (Fig.2.2.4.1):-

1) the western 'inner islands' of Buj, Tengah, Kaimeer, Kur, Wonin and Fadol;
2) the islands south of Tayandu Island in the Tayandu Group;
3) the islands north of Kai Kecil as far as Maas;
4) the many small islands south west of Kai Kecil including Kai Tanimbar, Utir, Ur and Nai;
5) the north and south of Kai Besar.

2.2.4.1 Bouguer Anomaly Features.

In general the Bouguer anomaly field in the Kai Islands region is dominated by high, positive values (+170 to +200mGal) over the margin of the Weber Deep and Kai Besar, separated by negative values (-20mGal) in the Tayandu Group, resulting in two steep, negative gradients converging on the Tayandu Group (Figs.2.2.4.1 & 2.2.4.2).

All regional Bouguer anomaly maps (c.f.Bowin et al,1981) show a steep, eastward negative gradient at the edge of the Weber Deep, with peak values reaching up to +200mGal. This negative gradient produces values of +15 to 0mGal over the 'inner islands' of Kur, Wonin, Fadol etc., with contours trending approximately N-S except in the north on the islands of Kaimeer, Tengah and Buj where contours turn in a NE-SW direction. Bouguer anomaly values are some 10mGal lower than indicated by regional marine surveys, which suggests

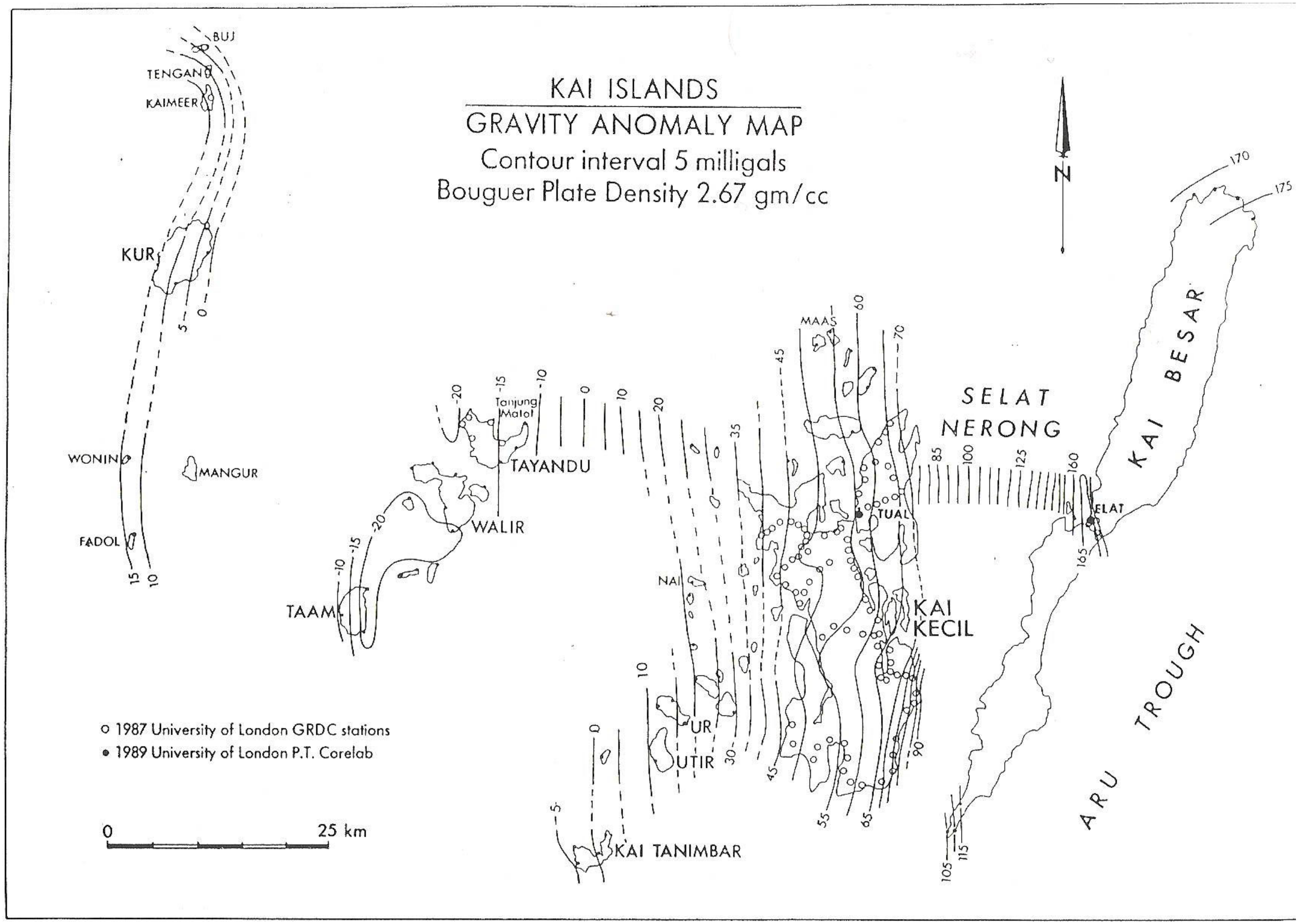


FIGURE 2.2.4.1 Kai Islands Bouguer anomaly map

that the Australian continental crustal boundary may lie even further west of the 'inner islands' than previously thought.

Anomaly values decrease further to -10mGal on the west coast of Taam in the Tayandu group, giving an average anomaly gradient of -1mGal/km between the 'inner islands' and Taam. West to east across Taam the gradient is approximately -8mGal/km, reaching values less than -20mGal. From Walir the gradient turns positive to the east so that by the east coast of Tayandu Island values are again at approximately -10mGal.

Between Tayandu Island and Kai Kecil, no details are available on the gradient, but N-S trending contours from -5 to 25mGal have been drawn on the map reflecting the general trend across the Kai Islands. South of this area the islands of Kai Tanimbar, Utir, Ur, and Nai, to the south-west of Kai Kecil, have Bouguer anomaly values in the range 0 to 45mGal, defining an increasingly steep, positive gradient towards Kai Kecil.

West to east across most of Kai Kecil the gravity field increases steadily at approximately 1mGal/km but in the area bordering Selat Nerong in the south the gradient is 4mGal/km and the Bouguer anomaly reaches values in excess of +90mGal.

Across Selat Nerong to Kai Besar there is a further increase to +165mGal at Elat in the middle of the island. Values in the south of the island are in the range +105 to +115mGal suggesting that the gradient shown across Selat Nerong (Fig.2.2.4.1) is broadly correct. Anomaly values of +170 to +175mGal are found on the north coast of Kai Besar. The few stations on Kai Besar are in close agreement with work done by Jezek (1976).

On the Bouguer anomaly map of Indonesia (Green,1979) the Bouguer anomalies around the islands are shown as decreasing to about +100mGal to the north of Kai Besar and to about +40mGal to the south. The only continuation of the very high values is on Manggawitu island, south of Irian Jaya. Overall the high values on Kai Besar are isolated from other positive trends although it should be remembered that the regional contours are based on a rather small number of ship tracks. The gravity anomaly field for this region suggests that between the Weber Deep and Selat Nerong there is a block of Australian continental crust which is separated from similar material under the Aru Trough by a major dislocation passing through the strait.

2.2.4.2 Cross-section modelling, Kai

The model for the Kai Islands (Fig.2.2.4.2) used in this chapter is based on modelling conducted immediately after the 1987 and 1989 surveys.

The polygon sections used to model the gravity field (Fig.2.2.4.2) were kept as simple as possible, and may therefore in some places appear to be geologically unrealistic. The calculated field is dominated by the mantle material close to the surface under Kai Besar and the Weber Deep.

The east-west profile starts in the east at the margins of the Aru Trough, runs westward through Elat on Kai Besar, crosses Selat Nerong to Tual on Kai Kecil and from there continues west to the island of Tayandu. The line then turns WNW towards the island of Kur before ending over the margins of the Weber Deep (Fig.2.1.1.1). Land data used in modelling are taken from the 5mGal contours on the simple Bouguer anomaly map (Fig.2.2.4.1). Marine values have been taken from the map prepared by Bowin et al (1980). The polygons used are listed and defined in Table 2.2.2.4.1.

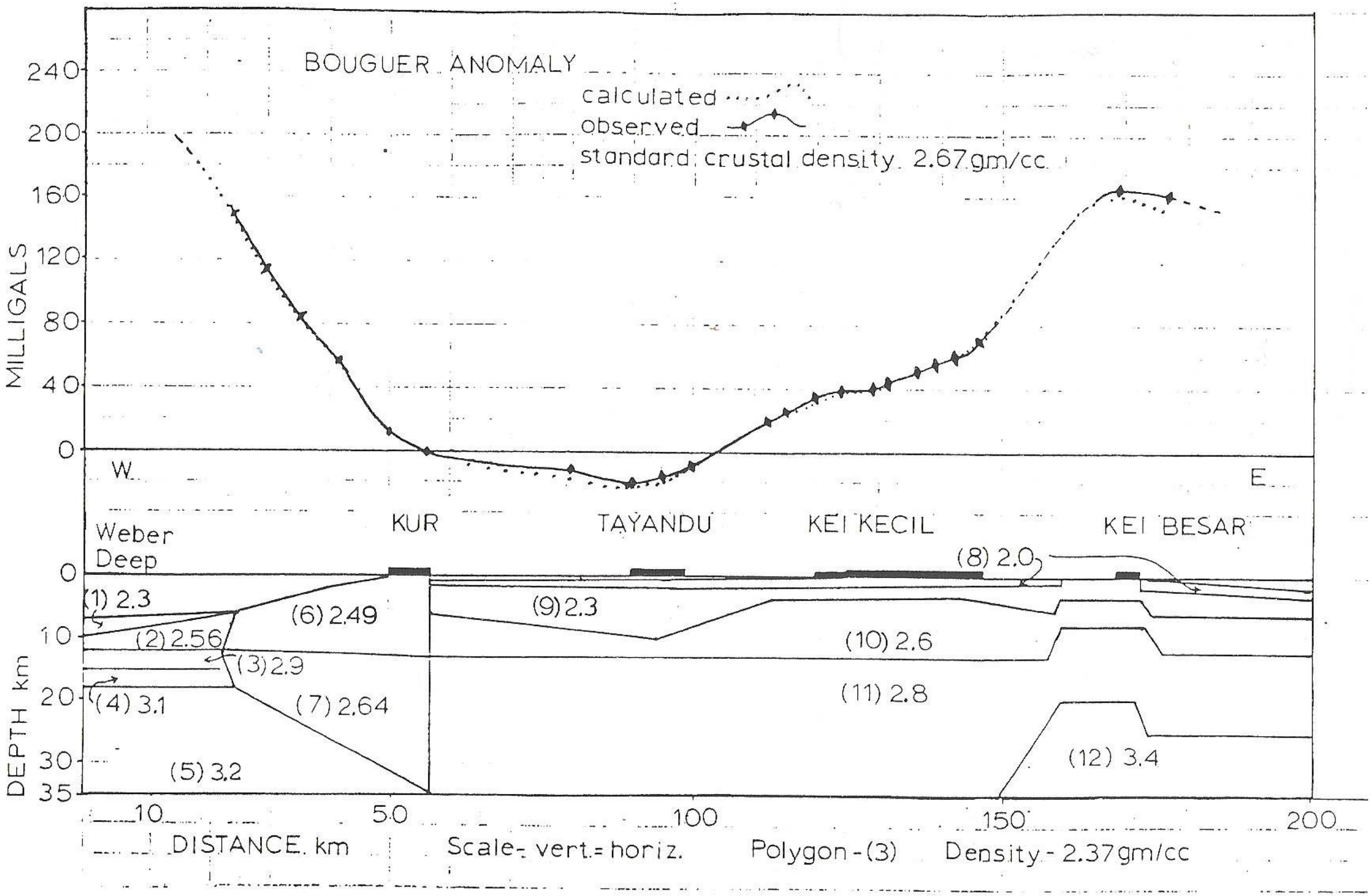


FIGURE 2.2.4.2 Kai Islands gravity model

The gradient from Kai Besar to Tayandu is fairly well controlled by land data, and has been modelled by simply postulating shallow mantle at the margins of the Aru Trough and under Kai Besar. This approach is supported to some extent by geological observations on Kai Besar where the Miocene and Eocene moderately tilted strata have risen along a series of north-south normal faults. The dense mantle rocks near the surface cause the high values on Kai Besar and the steep gradient as far as the Tayandu Islands.

Over Kai Kecil the observed regional field is dominated by the effect of the shallow mantle beneath Kai Besar. However, there are short wavelength variations that must be attributed to variations in the depths and densities of near-surface rocks. Specifically, the generally N-S oriented anomaly contours show the effects of near surface variations near the strait that separates Kai Kecil from Kaidulah, and also around the elongated N-S inlet on the west coast of Kai Kecil. As coral reefs have been elevated so uniformly throughout the Kai Kecil group, it is thought that these gravity variations, both over linear features, are probably due to wrenching rather than thrusting or normal faulting. The form of the Bouguer anomaly contours suggests differential NNW-SSE sinistral movement, but no systematic geological mapping has been conducted on the islands to confirm or disprove this suggestion.

Between Selat Nerong and the Tayandu Islands the short wavelength variations in the calculated field are produced by varying the depth and thickness of the unconsolidated surface sediments (Polygon 8) and the imbricated sediments (Polygon 9). This results in an increase in the thickness of the upper crustal sediments (Polygon 10) under Kai Kecil before they thin midway between Kai Kecil and the Tayandu Islands.

Bouguer anomaly values on Tayandu range from -10 to -20mGal, with a gradient suggesting that the field is still controlled to a large extent by the raised mantle under Kai Besar. However, the raised mantle under the Weber Deep has also to be taken into account and the observed negative values on Tayandu can be modelled only by increasing the thickness of the imbricate layer (Polygon 9) to a depth of 12km or by introducing new low-density polygons. Part of the observed negative field may be due to the presence of shale and associated diapirs in this region. The Tayandu Islands are reported to have active mud volcanoes and the shape of Tayandu itself is also suggestive of large scale mud volcanism, with the two large, relatively deep water, embayments in the northern coast being possible sites of former volcanoes, now eroded away. The small present-day mud volcano at Tanjung Matot was probably more active in the past, judging by the presence of mud volcanic ejecta embedded in raised coral blocks around its margins. The ejecta are similar to those from Tanimbar mud volcanoes, with Triassic sandstones, Jurassic ironstones and younger carbonates. It would appear that the crust under the Kai Islands is similar to that under the Tanimbars.

Westwards from the Tayandu Islands to Kur and the other 'inner islands' the observed field is inferred to have a gradient of 1 to 2mGal/km, reaching 0mGal at the east coast of Kur. There may be local variations in the gravity field between the islands but these can only be defined by analysis of marine gravity data. There are outcrops of metamorphic basement rocks of supposedly Australian affinity on Kur and Fadol (Charlton, Barkham, de Smet, 1989). West of Kur the observed field has been modelled by two polygons (6 and 7,Fig.2.2.4.2), which may represent a boundary zone between the continental and oceanic crusts. Within this region much tectonic activity is to be expected including strike-slip faulting and overthrusting of the margin of the Kai block, thereby bringing basement rocks to the surface. All the 'inner islands' have experienced rapid uplift resulting in at least five raised terraces, some of which are marked by steep cliffs elongated north-south, suggesting that the zone of uplift is similarly orientated.

One of the most interesting constraints on the modelling was the need to extend the lower crust under Kai Kecil and Tayandu down to the model limit of 35km. This is a greater depth than has been indicated in previous models of the region. However, the other published models have been of areas further to the south (Bowin et al, 1980; Schluter and Fritsch,1985) in regions that are gravitationally and geologically dissimilar to the Kai region. Figure 2.2.4.3 shows a model in which the mantle depth below Kai Kecil and Tayandu has been set equal to that under the Aru Trough. This model assumes that the former continental margin in the region between Kur and Selat Nerong thinned as it was translated and rotated during migration northwards around the Banda Sea micro-plate. To obtain the necessary calculated Bouguer values the Australian imbricated units have been extended down to a maximum depth of 18km, and the lower crust has been thinned considerably. The densities of the boundary zone (Polygons 6 and 7, Fig.2.2.4.3) have been decreased to 2.4 and 2.52g/cc respectively. The observed negative values in the Tayandu group can be modelled only by introducing a polygon (Polygon 13) with a density of 2.0g/cc, representing shale and associated diapirs.

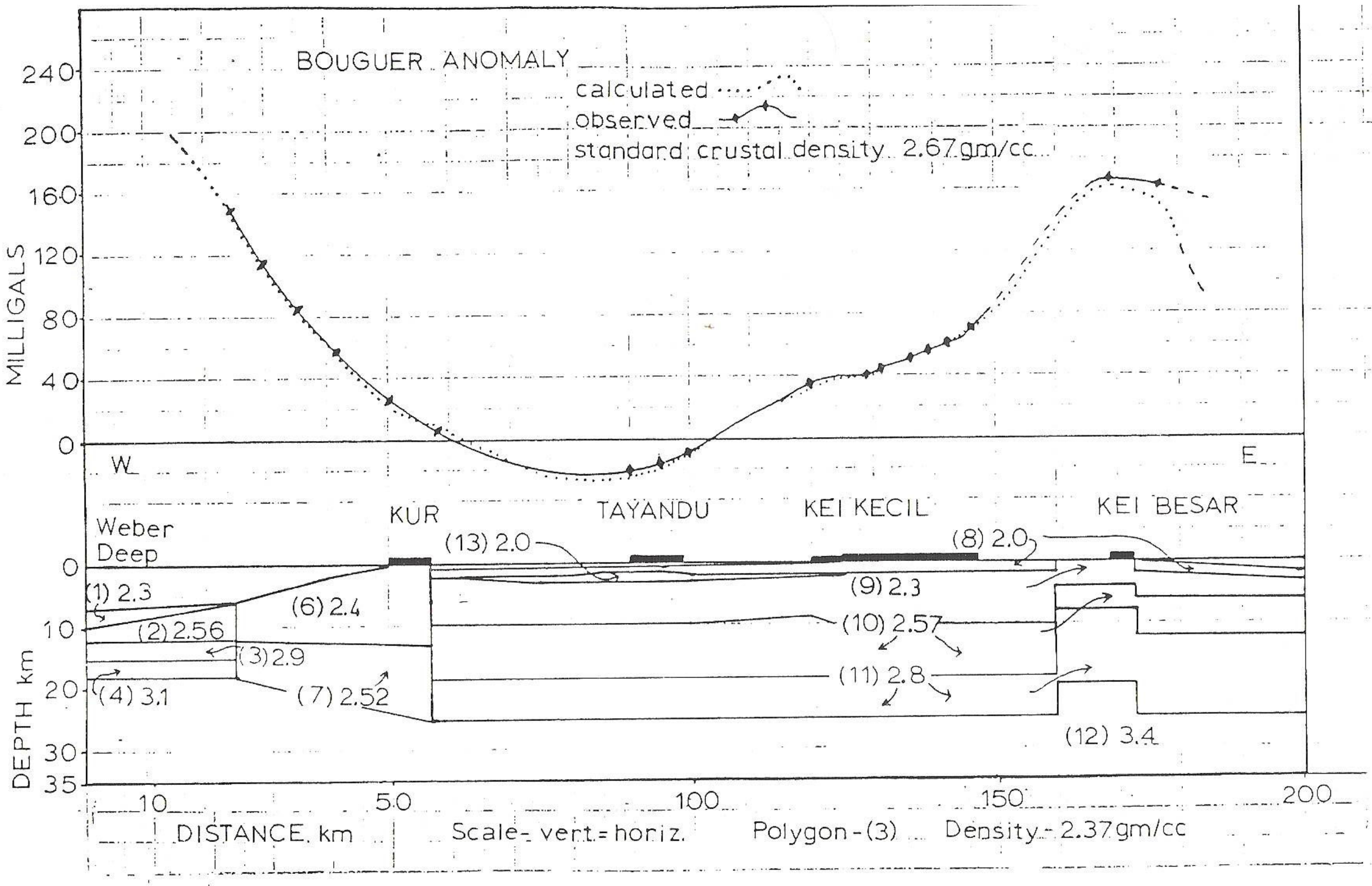


FIGURE 2.2.4.3 Kai Islands gravity model - mantle at 25km

TABLE 2.2.2.4.1

POLYGON NUMBER	DENSITY(g/cc)	DESCRIPTION
1	2.3	Weber margin sediments
2	2.56	Weber margin consolidated sediments
3	2.9	Weber margin oceanic layer 3
4	3.1	Weber margin oceanic layer 4
5	3.32	Oceanic mantle
6	2.49	Weber deep - Australian crust upper transition zone
7	2.64	Weber deep - Australian crust lower transition zone
8	2.0	Australian surface sediments
9	2.3	Australian imbricate sediments
10	2.6	Australian underplated and upper crustal rocks
11	2.8	Australian lower crust
12	3.4	Aru trough mantle

2.2.5 DISCUSSION AND CONCLUSIONS

It is now generally accepted that the Banda Arcs were created by the subduction of the 7.5cm/yr north-north-easterly moving Australian plate beneath the relatively static Banda Sea 'micro-plate'. Geological field observations and seismic reflection data suggest that subduction of the Australian plate under the Banda Sea has now ceased in the Tanimbar region but that convergence continues. The cessation of subduction and the resulting convergence-related compression, coupled with strike-slip activity, has been responsible for the emergence of the islands.

The Bouguer anomaly fields of Timor and Tanimbar have similarities which reflect their respective structural positions in the Banda Arc. The field in Timor declines from positive values (+120mGal) in the north via a very steep gradient to negative values (-40mGal) in the south, before increasing to approximately +50mGal south of the Timor Trough. This profile is common to the southern Banda Arc from West Timor to Tanimbar. The negative values north of the Timor-Tanimbar Trough are due to the increasing thickness of the forearc wedge, while the presence of dense volcanic/oceanic rocks north of the forearc, in part, causes the steep, positive, northerly gradient. The Tanimbar Islands land surveys have mainly measured the negative part of this common profile. However, marine data from around the islands may show the complete profile, particularly the steep positive gradient to the north, the beginning of which (+10mGal) may have been measured in the 'inner islands'.

The history of plate movements can be best be understood by subdivision of the geological units into autochthonous, parautochthonous and allochthonous units (Audley-Charles, 1986). The autochthonous rocks are defined as having been formed where they are presently sited. They include all units younger than late Pliocene- early Pleistocene, a conclusion based on the field observation that units younger than mid-Pliocene are not strongly deformed. Geohistory curves (de Smet et al, 1989) indicate that the main episode of deformation, which was presumably the collision of the Australian continental margin with the subduction zone, occurred in the Pliocene and was complete by the beginning of the Pleistocene. The autochthonous units exposed on the islands include the products of mud volcanism (Bubuan Mud Complex), raised terraces of fringing coral reefs (Saumlaki Formation), all alluvial deposits and the Batilembuti Formation. The latter is probably equivalent to the upper most sequence of undisturbed reflectors that drape the imbricated units seen in the BGR lines (Schluter and Fritsch 1985) over the Tanimbar Trough. Since the early Pleistocene the autochthonous units have been passively uplifted on the backs of overthrusting parautochthonous blocks.

The parautochthonous units are defined as having moved only small distances since their deposition. They are all older than late Pliocene-early Pleistocene, and formed part of the Australian rise, slope and shelf sequence prior to imbrication and underplating within the forearc. Consequently, all those units mapped on the main island of Jamdena, other than those attributed to the autochthon, can be considered to be part of the parautochthon. Following collision, some of these units at depth in the accretionary wedge were compressed and were then overthrust onto the continental margin. Parautochthonous units make up Polygons 10,11 and 12, and form the major constituents of Polygons 7,8,and 9 in Figure 2.2.3.3.2. Polygons 7 and 8 include allochthonous rocks.

The allochthonous rocks are distinguished from the parautochthon on the basis of their overthrusted and out-of-sequence position. These overlie the Jamdena parautochthon in the Selat Jamdena and 'inner islands' region. Units include the Permian Selu Formation, the Triassic Wotar and Laibobar Formations, the Jurassic shales and the Cretaceous Ungar

Formation. The allochthonous oceanic metabasics, also found in the 'inner islands', and other allochthonous units do not outcrop on Jamdena or in the main part of the Kai block.

The allochthonous units of Tanimbar are similar in position and character to the nappes of northern and central Timor, although those in Tanimbar have not been overthrust to the same extent. This is probably due to the more oblique collision in the Tanimbar area compared to that in Timor.

In Timor, the collision of the Australian Continental margin with the subduction zone caused the older and deeper units of the forearc to be overthrust from the north onto the parautochthon of central Timor. These nappes range in age from the Permian to the Miocene. At a later stage, and possibly continuing today, nappes of oceanic material have been emplaced onto the northern coast of Timor. This later activity may have coincided with the northward displacement of Timor along major sinistral strike-slip faults as the Australian craton continued to converge on the forearc. A comparable tectonic development probably occurred in the Tanimbar Islands.

The development of the Tanimbar Islands is summarised in the simple structural map (Fig.2.2.5.1) and the crustal scale cross-section (Fig.2.2.5.5). These are based upon examination of Landsat images, all the gravity anomaly maps, geological and topographical information and gravity modelling.

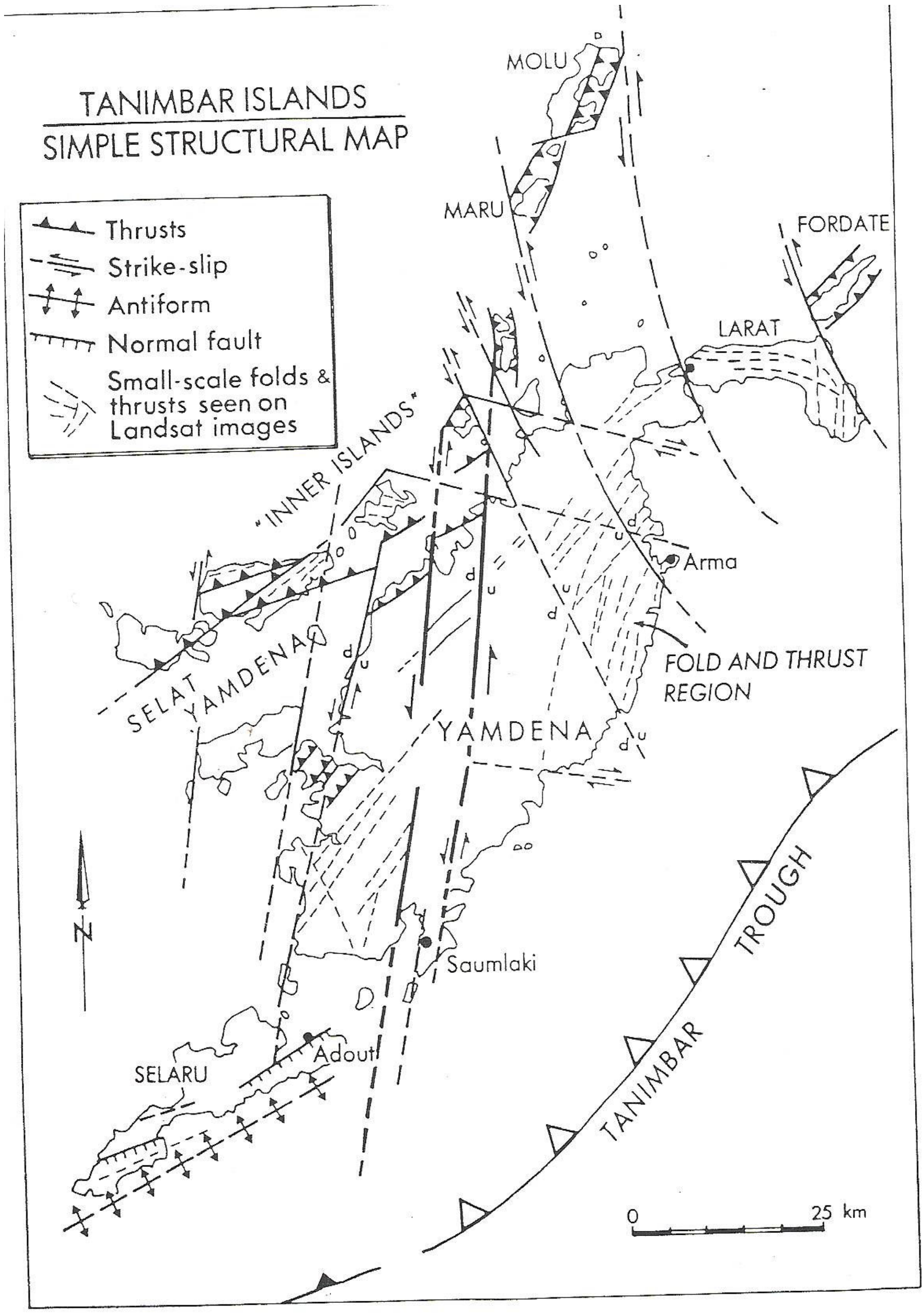


FIGURE 2.2.5.1 Tanimbar Islands simple structural map

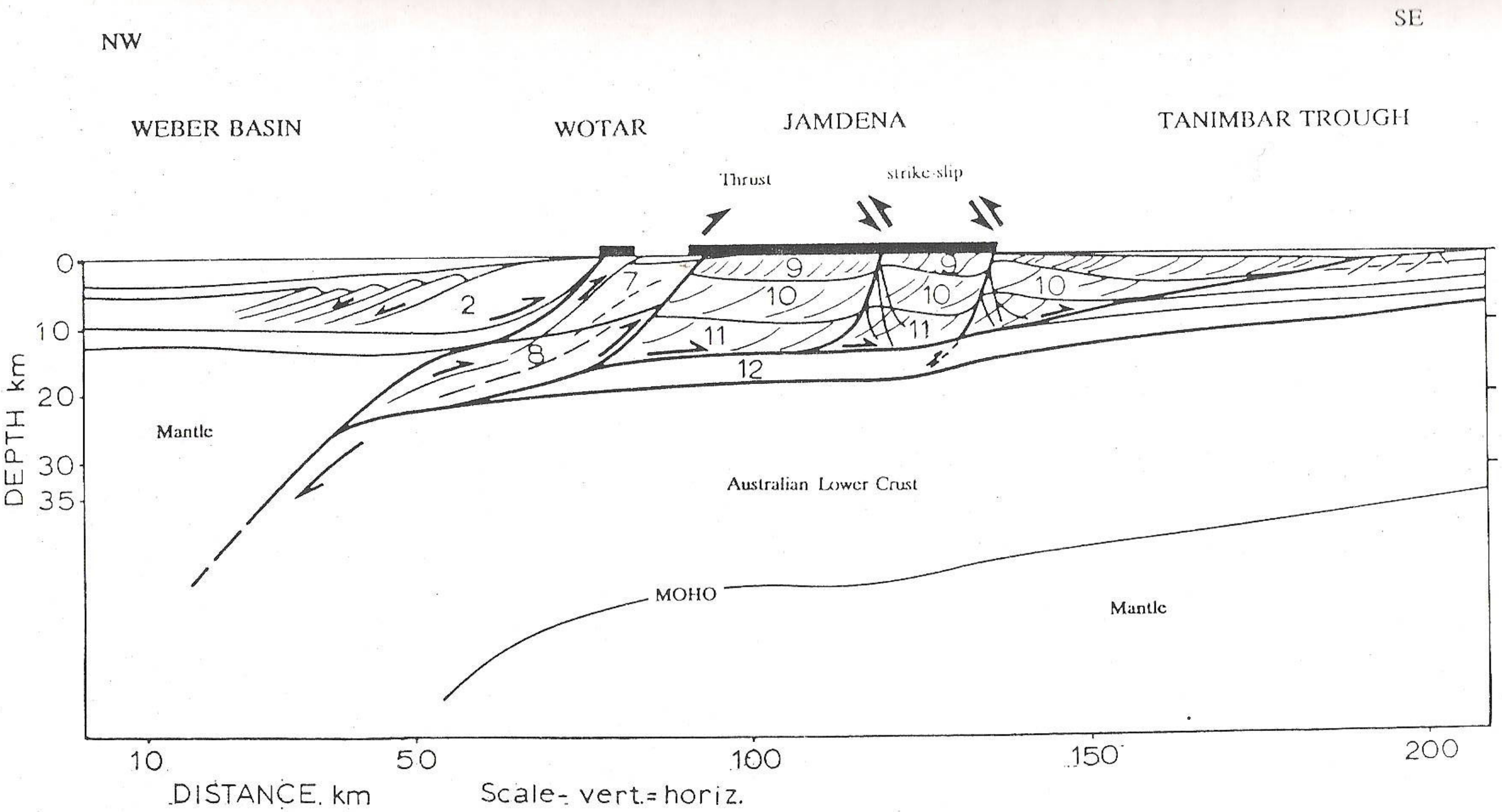


FIGURE 2.2.5.5 Crustal scale structural cross-section through the Tanimbar Islands.
Line of section and block numbers identical to the gravity model

Prior to the final suturing of the Australian Continental margin with the forearc, a 150km wide imbricate wedge was developed, consisting of Australian rise, slope and shelf sediments of Permian to Miocene age. After collision, subduction may have stopped, but convergence continued resulting in the overthrusting of the 'inner islands' allochthon onto the Jamdena parautochthon. Numerous strike-slip faults and wrench zones developed which have displaced the Tanimbar Islands north-north-eastward. Total displacement may amount to 40 to 50km in the 'inner islands' (Fig.2.2.5.1), thereby creating a sinuous Bouguer anomaly pattern, similar to that over northern Timor. Further to the south over the eastern coastal region of Jamdena the strike-slip faults are the site of differential uplift of blocks within the forearc due to either overthrusting along the fault zones, and/or the juxtaposition of varying structural levels of the forearc. These blocks and associated strike-slip faults cause the steps in the Bouguer anomaly field in this area (Figs. 2.2.3.3.2 and 2.2.5.5).

The strike-slip activity is here interpreted to be elongating the Tanimbar block in a north-north-easterly direction causing the sharp curvature of the Banda Arc in this region. The Australian craton is also moving in a similar direction so that the now inactive Tanimbar subduction trough parallels the east coast of Jamdena. The structural map (Fig.2.2.5.1) shows the main inflections in the trough which appear to coincide with continuations of the main strike-slip and wrench zones which cut across Jamdena and the 'inner islands'. This is particularly evident for the main wrench zone of Jamdena which is thought to strike in a NNE-SSW direction between Saumlaki and Selaru Island. The northward displacement of blocks in the Tanimbar Islands and inflections in the Tanimbar Trough are probably related to the continuing oblique convergence of the Australian craton on Eurasia. The combined effect is to cause the curvature of the Banda Arc in this region.

To the north-east of the Tanimbar Islands there is a major bathymetric trough which strikes NW-SE and links the Weber Deep and the Aru Trough and which is probably the result of earlier northward translation of the Kai Islands crustal block away from the Tanimbar block. It is possible that the trough now marks the southern limit of the zone of regional extension which covers an area from the Weber Deep, in the west, to the Aru Trough in the east. South of this trough compression tectonics dominates the Tanimbar block, while to the north the earlier effects of compression in the Kai block have been overprinted by the later extensional tectonics (see section 3.2.3).

Allochthonous units (Mesozoic sediments and oceanic metabasics) are only found in the 'inner islands' of Tanimbar and Kai and not, apparently, south of Selat Jamdena or in the main part of the Kai group. Their absence on Jamdena, together with the form of the 'inner islands' arc, suggests that the formation of allochthonous nappes in Tanimbar is being inhibited by some factor that does not operate in either Timor or Seram. This factor may be the oblique angle of convergence in the collision zone in this region. The converging plates are more likely to slide past each other, in a sinistral sense, and the forces produced will be insufficient for nappe emplacement. The main site of sinistral strike-slip in the Tanimbars is Selat Jamdena, but varying amounts of wrenching will occur south of this region within the parautochthon, causing deformation within the overlying autochthonous units.

Charlton, Kaye et al (unpublished manuscript,1988) have examined extension in the Weber Deep-Kai Islands-Aru Trough region using their own geological field observations and this studies gravity data combined with gravity, bathymetric and shallow seismic data from regional compilations (e.g.Bowin et al,1980). The Aru Trough is interpreted in terms of a Wernicke-type extensional model (Fig.2.2.5.6), linking upper brittle crustal extension, primarily under the axis of the Aru Trough, with ductile extension of the lower continental crust beneath Kai Besar and the western Aru Trough resulting in dense mantle material closer to the surface in this area. The horizontal extension implied by this model is 35km,

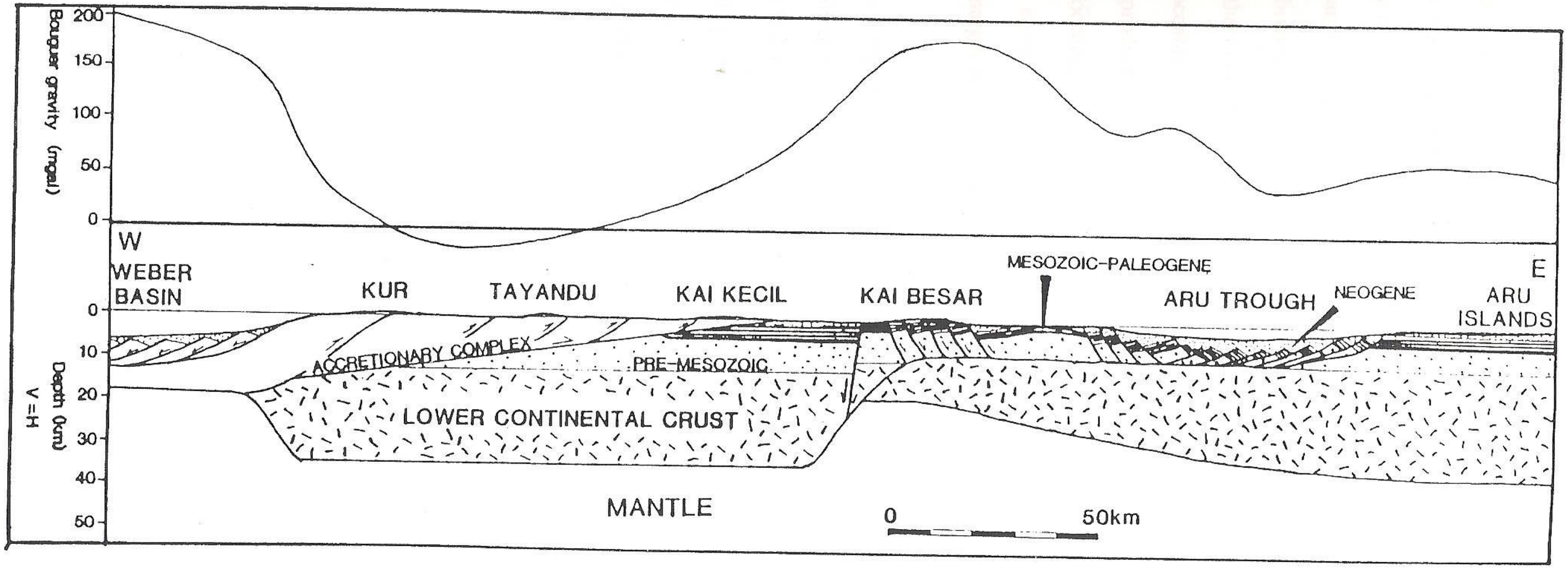


FIGURE 2.2.5.6 Crustal scale structural cross-section through the Kai Islands.

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indicating 40% extension (=1.4) over the region from Kai Besar to the eastern flank of the Aru Trough. The area from Kai Kecil to the 'inner islands' of Kur and Fadol etc is considered to be an imbricate stack of Australian marginal sediments overlying continental basement. Further to the west, the Weber Deep was interpreted by Bowin et al(1980) as the site of depressed oceanic crust. Charlton et al interpret the thinner crust beneath the Weber Deep as the product of extreme crustal attenuation resulting from east-west extension of marginal/oceanic crust which previously formed the innermost part of the eastern Banda forearc complex. Another possibility is that the Weber Deep is underlain by a former volcanic margin to the Australian continent.

It seems likely that the complex interplay of the main converging units upon the eastern Indonesian region resulted in considerable strike-slip activity and consequent rotation of crustal blocks (e.g. the Kai Islands). Subsequently, and after final suturing in Timor and Seram, an extensional phase became dominant which has overprinted the earlier compressional tectonics. The Tanimbar crustal block is still involved in localised compressional tectonism due to its position at the major inflection of the Banda Arc.

PART THREE

REGIONAL DISCUSSION AND CONCLUSIONS

CHAPTER 3.1

OPHIOLITE TERRAINS: THEIR ORIGIN, EMPLACEMENT AND SIGNIFICANCE TO EASTERN INDONESIA

3.1.1 BASIC CONCEPTS AND RECENT CONCLUSIONS

The purpose of this chapter is to review other areas in SE Asia that are similar geologically and geophysically to Eastern Indonesia, and which may offer insights into the mode of formation of Timor and Tanimbar in particular.

Ophiolite complexes are widely regarded as fragments of oceanic crust and upper mantle, obducted onto continental margins. Their origin, whether oceanic crust, island arc or marginal basin, and their mode of emplacement, are still debated. Figure 3.1.1.1 is a simplified and idealized cross-section of an ophiolite. It is beyond the scope of this thesis to include a description of all the variations on Figure 3.1.1.1. that have been documented, but pertinent differences will be mentioned.

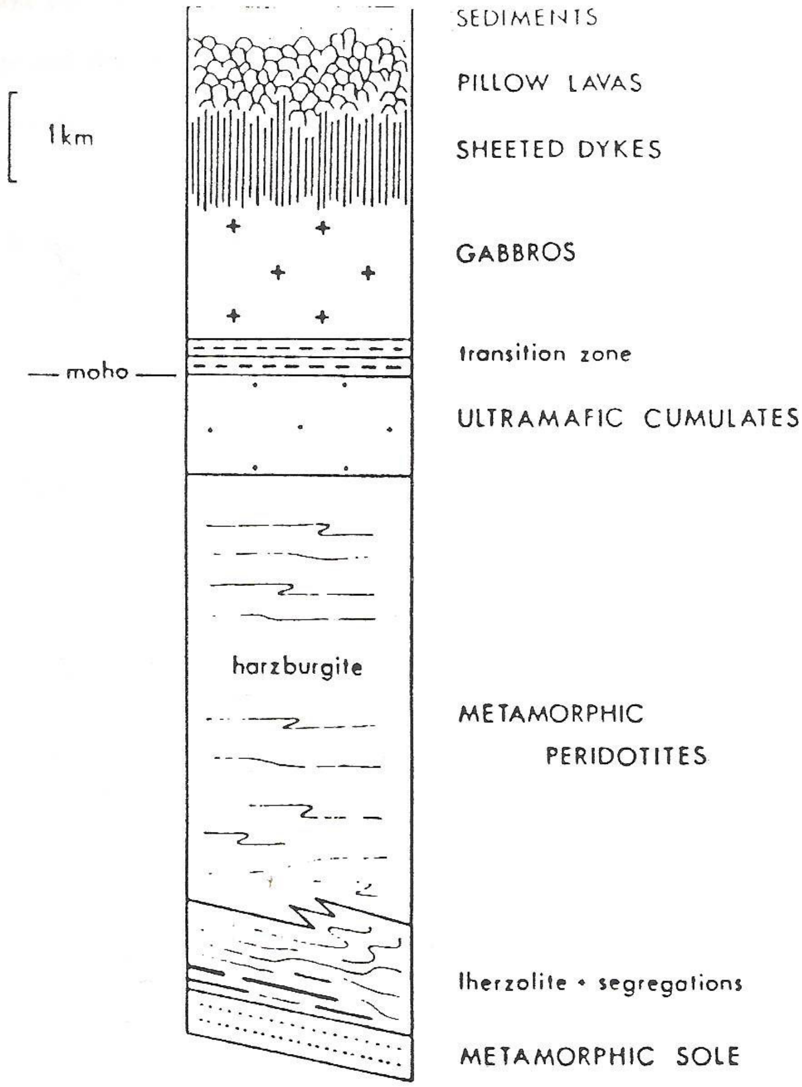
There have been many theoretical models of emplacement which have been proposed:-

a) Collision-subduction-accretion (Church and Stevens 1971; Dewey and Bird 1970,1971; Dewey 1976; Smith and Woodcock 1976; Malpas and Stevens 1977; Welland and Mitchell 1977; Gealey 1977; Searle and Malpas 1980)

b) Gravity sliding processes (Williams and Smyth 1973; Glennie et al 1973; Stonely 1975; Coleman 1977)

c) Gravity spreading processes (Elliot 1976; Searle and Malpas 1980)

d) Transform-fault processes (Brookfield 1977; Karson and Dewey 1978).



Simplified and idealized cross-section of an ophiolite showing internal components, including positions of lherzolites and mafic segregations in the mantle sequence (metamorphic peridotites) and metamorphic sole.

FIGURE 3.1.1.1 Simplified and idealized cross-section of an ophiolite showing internal components, the mantle sequence and metamorphic sole.

It is now widely accepted that ophiolite complexes can arise from a variety of geological settings and that modes of emplacement can include, at different stages, all four of the above mechanisms.

The following phenomena were noted by Searle and Stevens(1984) to accompany ophiolite emplacement:

1) Collapse of the continental margin prior to emplacement.

2) A rapidly deepening foredeep on the continental margin accumulating a great thickness of syn-orogenic flysch.

3) A subduction zone.

4) Underthrusting of oceanic sediments and volcanics beneath the ophiolite producing a dynamo-thermal metamorphic sheet.

5) Regional uplift of the ophiolite and sinking of the foreland-migrating foredeep causing a regional slope dipping towards the continent, followed by gravity spreading and the thrusting of oceanic sediments and ophiolite onto the continental margin.

Woodcock and Robertson(1984) examined a number of Tethyan ophiolites and pointed out that no two areas have an identical geometry, or history, and that comparisons can not support any single model of ophiolite emplacement. They also examined dip-slip and strike-slip modes of emplacement and concluded that these two modes represent end members of a spectrum of mechanisms and that both could operate in the same area at different stages.

Spray(1984) notes that ophiolites are generally <15km thick; have granulite metamorphic soles requiring temperatures that are found at the isothermal boundary between oceanic lithosphere and asthenosphere; and that the age difference between ophiolite igneous crystallization and metamorphic sole formation is often <10my.

3.1.1.2 Tethyan, Cordilleran and Supra-Crustal Ophiolites

Tethyan-type ophiolites (Moores,1982) are typified by the association of nearly complete ophiolite nappes overlying a imbricated continental margin sequence. They are usually emplaced within 10Ma of their creation, formed from the upper plate, are commonly pre-orogenic in age, and are amongst the youngest rocks of many mountain systems.

Cordilleran ophiolites (Moores,1982) are usually created from the lower plate of a subduction zone or emplaced by strike-slip motion, parallel to Andean-type convergent margins. Cordilleran ophiolites form some of the oldest parts of accretionary terrains in many orogenic belts such as the North American Cordillera.

Supra-subduction zone (SSZ) spreading (Moores et al.,1984; Pearce et al.,1984; Hawkins et al.,1984; Leitch, 1984) is a mechanism invoked recently to explain the features of Tethyan-type ophiolites. The principal mechanism for SSZ spreading is trench retreat. This involves the evolution of a subduction zone controlled by the behaviour of the down-going plate, whereby as subduction proceeds, the down-going plate subsides vertically causing the trench to retreat away from the volcanic arc. This causes extension between the volcanic arc and the trench leading to the formation of new crust in this region. This new crust is then emplaced as ophiolite nappes by a later phase of compressional tectonics imposed by arc-continental collision.

3.1.2 THE OPHIOLITES OF PAPUA NEW GUINEA(PNG)

The northward-drifting Australian continental margin has collided with a number of island-arc systems during the Late Mesozoic and Tertiary. Consequently, large masses of ultramafic and mafic rocks have been emplaced along the northern and eastern margins of the main orogenic belt in PNG (Fig.3.1.2.1). There are three main ophiolite regions; the Papuan Ultramafic Belt (PUB), the Marum Complex and the April Ultramafics. Only the first two will be discussed in detail.

The PUB comprises the full ophiolite suite and is by far the largest ophiolite complex in PNG occupying large areas of the Papuan Peninsular. The sialic core of the Papuan Peninsular (Fig.3.1.2.2) consists of low to medium grade metamorphic rocks of Mesozoic age and basalt lava, partly Eocene and partly Late Cretaceous. These units are overthrust by the PUB with basal ultramafics overlain by Cretaceous gabbro and submarine basalts, which are intruded by Eocene tonalites. The Eocene tonalites are probably related to Eocene andesite volcanoes. Davies(1977) describes the structure as arcuate in plan dipping at 10-40 degrees in a generally easterly and northerly direction, bounded to the west and south by the arcuate Owen Stanley Fault and is disrupted by northwesterly-trending left lateral strike-slip faults. Possible Cretaceous sediments, to the west and north of the PUB, are metamorphosed in a classic Barrovian sequence (Barrow,1912) grading from garnet-bearing schist in the northeast to phyllites in the southwest (Davies,1977). The ophiolite is thought to be Jurassic and/or Cretaceous Pacific oceanic crust emplaced onto the Australian margin in the Early or Middle Eocene followed, or accompanied by, the cessation of subduction. The gravity field has been investigated by St.John(1967,1970), Milsom(1971,1973a and 1973b) and Finlayson(1977). Figure 3.1.2.3 is the gravity anomaly map for the area whose main features are a curvilinear low which coincides with the outcrop of sialic Mesozoic metamorphics and the pronounced highs associated with the ophiolite complex. The highs are consistently offset seawards

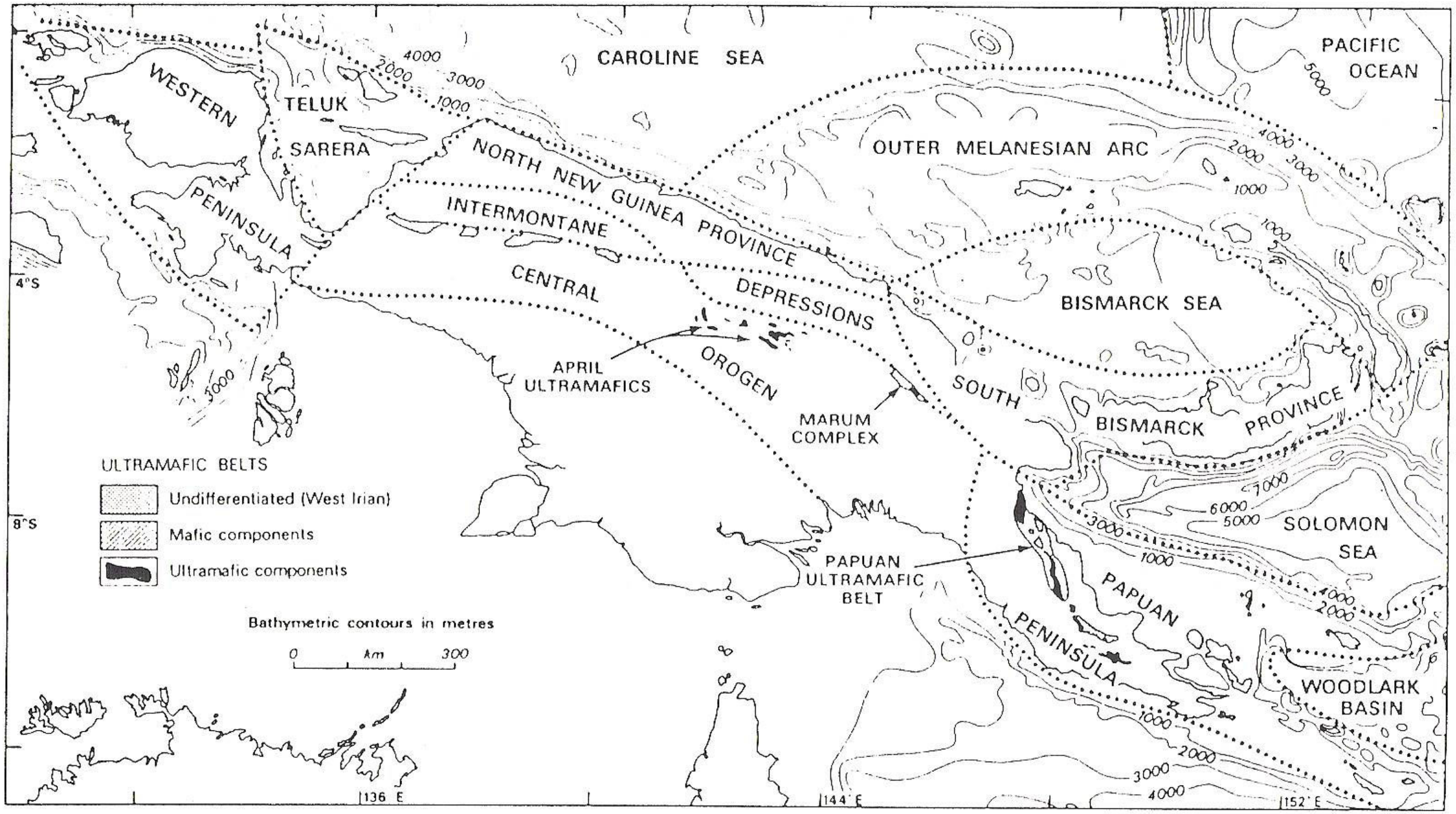


FIGURE 3.1.2.1 Main geological subdivisions of the New Guinea mobile belt, showing locations of the major ophiolites. (From Milsom,1984).

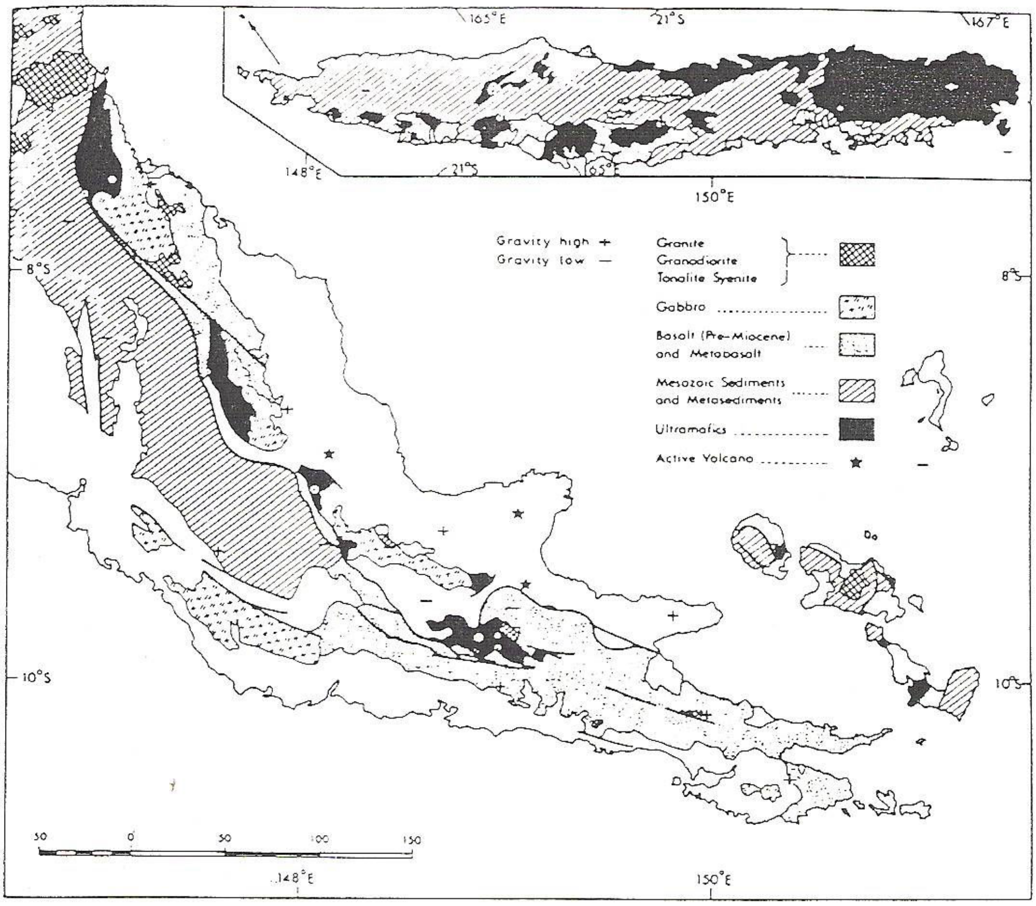


FIGURE 3.1.2.2 Simplified geology of the Papuan Peninsular, after Davies and Smith(1971). Inset: simplified geology of New Caledonia, after Lillie and Brothers(1970).

(northwards) from the ultramafic outcrop, a feature which is inferred to be due to the seaward dip of the ophiolite (Fig.3.1.2.4). North of the Tobriand Islands is a high anomaly region which is offset from the main PUB trend. This is considered by Davies(1977) to be due to displacement of the main ophiolite complex along a sinistral northerly striking strike-slip fault(s).

The Marum Ophiolite Complex (Fig.3.1.2.1) consists of mafic and ultramafic plutonic components which have overthrust basaltic rocks of tholeitic affinity. Tuffaceous argillites and greywackes that overlie the basalts contain dolerites and basaltic to andesitic volcanics (Milsom,1984). It is commonly believed that the Marum Complex is a segment of a former island arc emplaced between the Late Eocene and Middle Miocene. Very large gravity anomalies associated with the belt are offset northwards and eastwards indicating thrusting from that direction. The Marum Complex 'high' is bordered to the south by a 'low' probably due to a thickened crustal root below the central ranges. To the north is another 'low' due to the thick Neogene sediments in the Ramu Valley basin. Like the PUB, strong Bouguer anomaly highs are found over outcrops of the complete ultramafic and mafic sequence but not where the outcrops consist of only the ultramafic rocks. Milsom(1984) models the Bouguer anomaly field by a northerly dipping ultramafic mass which is overlain by a thick sequence of low-density sediments. This model supports an arc-continent collision but Milsom(1984) points out that the thin, ultramafic sheets may be more readily explained as oceanic overthrusts.

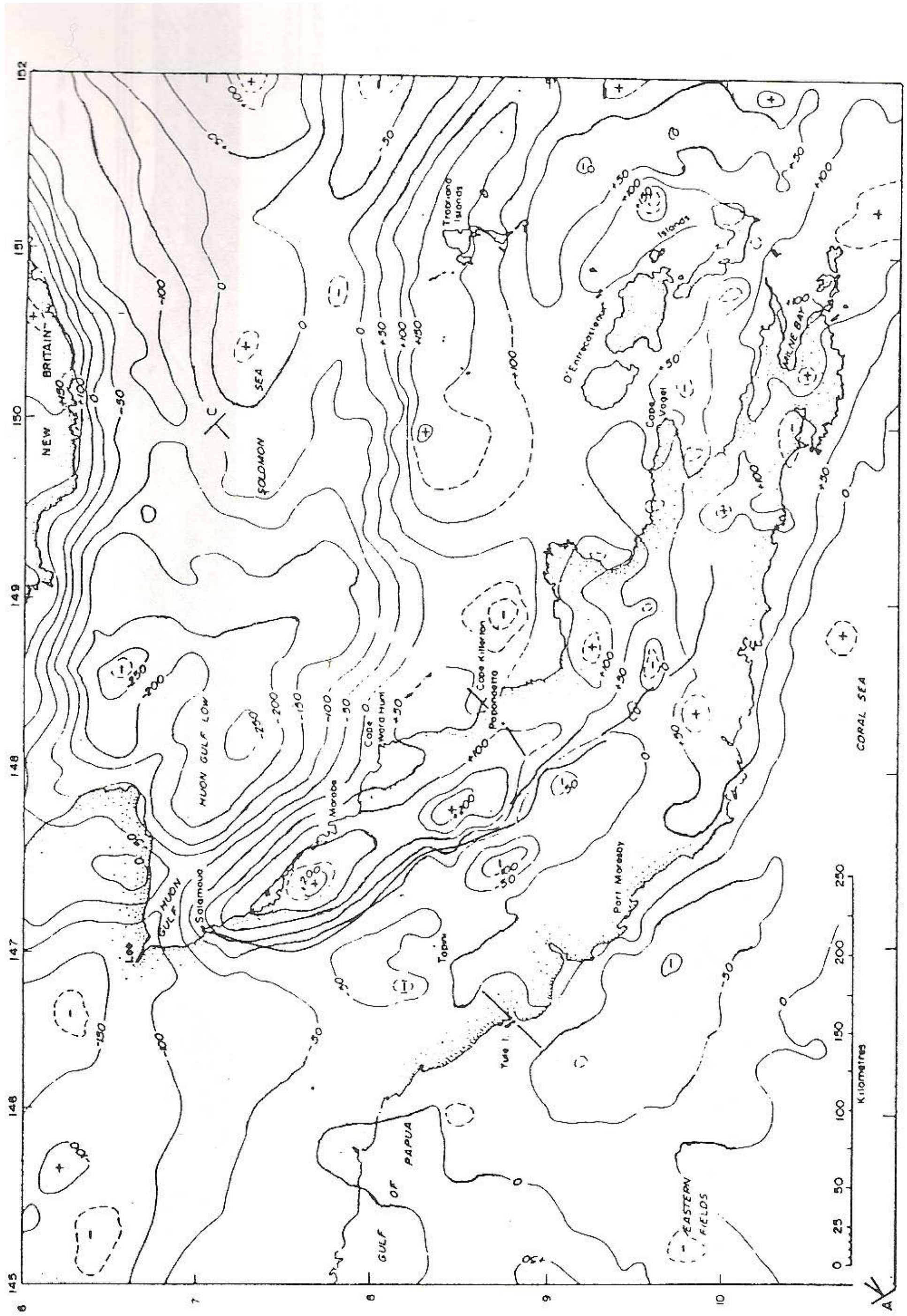


FIGURE 3.1.2.3 Gravity map of the Papuan Peninsular region, after Finlayson et al,1977. Free air anomalies off-shore and simple Bouguer anomalies on land. From Davies,1977.

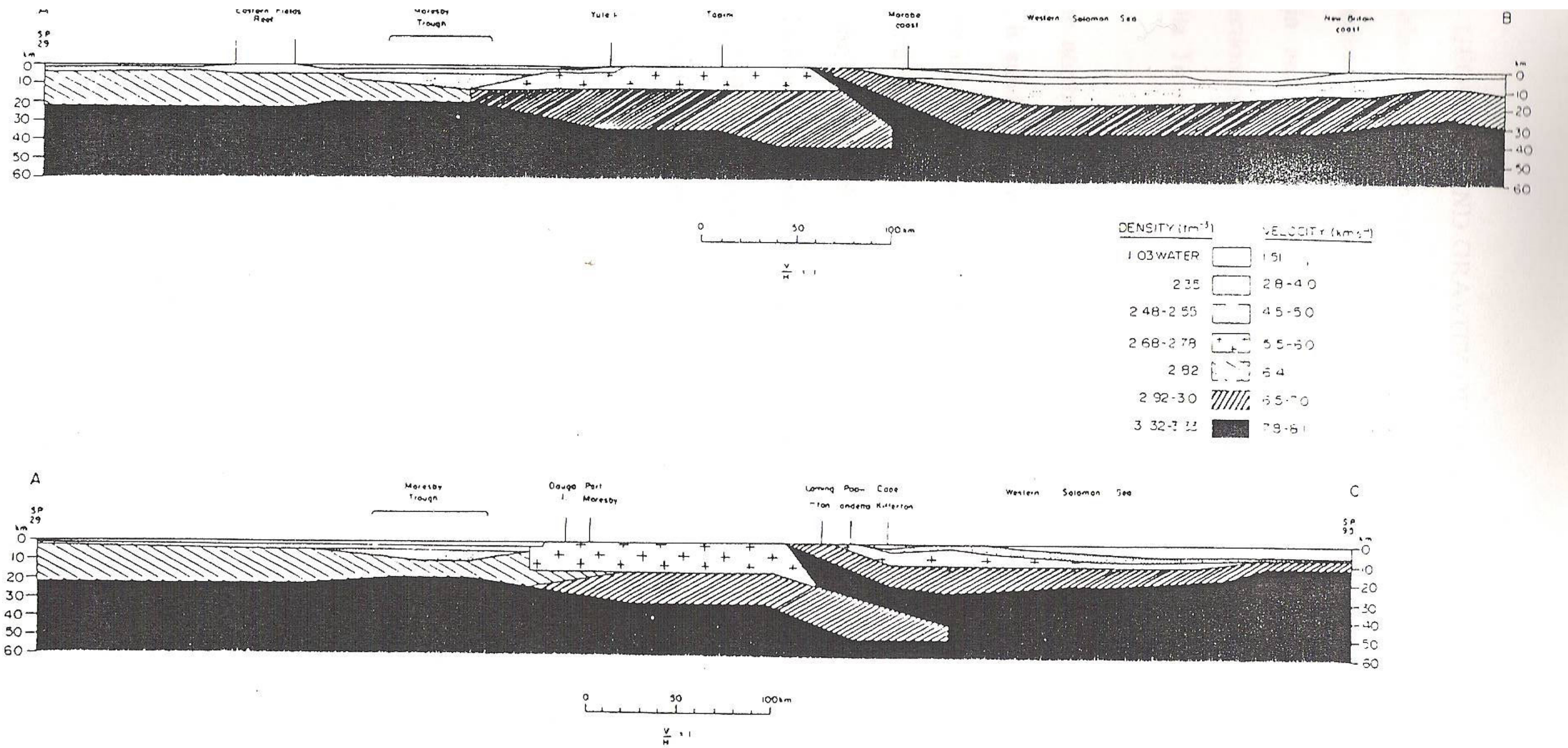


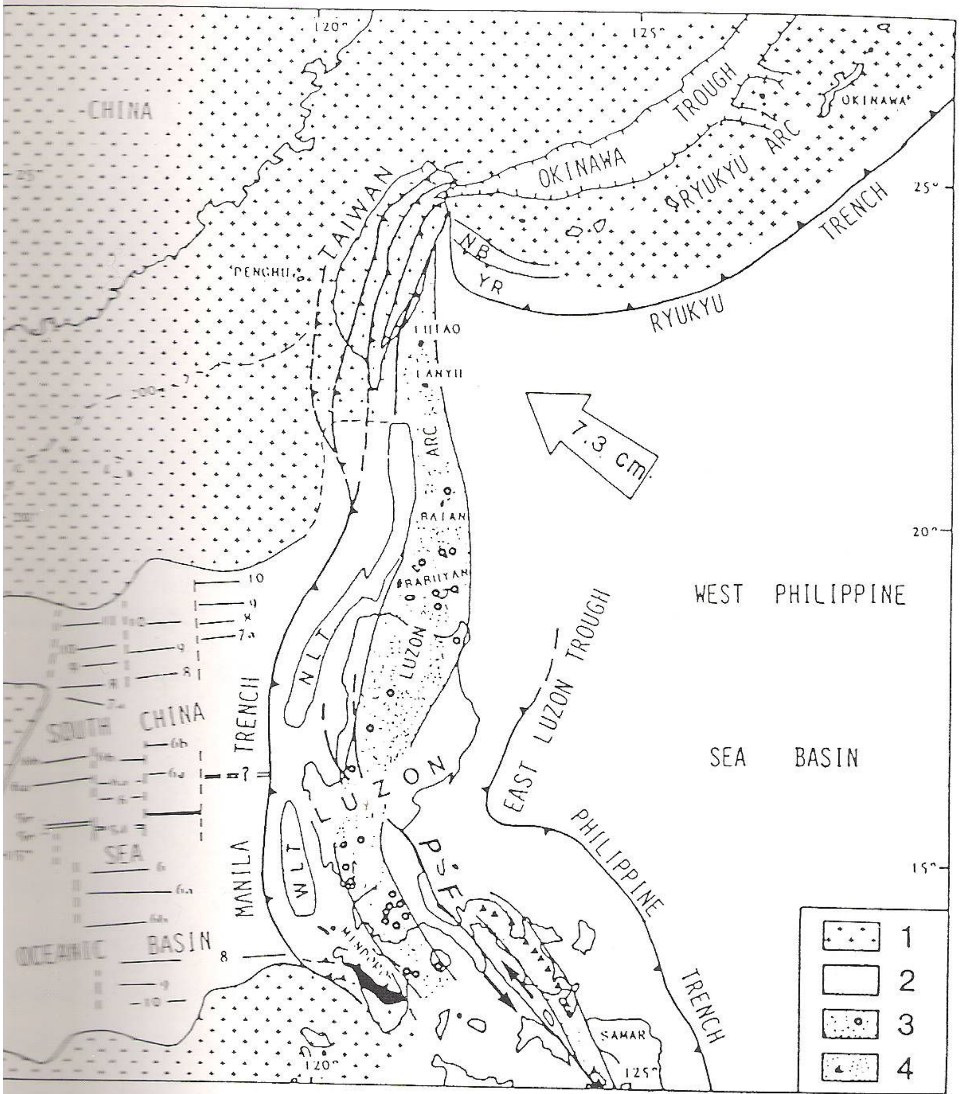
FIGURE 3.1.2.4 Cross-sections of the Papuan Peninsular showing structure based on seismic, gravity and magnetic data, after Finlayson et al, 1977. From Davies,1977

3.1.3 GEOLOGY AND GRAVITY OF TAIWAN

The island of Taiwan has a tectonic setting that may be analogous to the Timor and Tanimabar Islands. Taiwan lies at the junction of the Luzon Arc and the Chinese passive margin and results from the collision of these two units. The collision follows the subduction of the Oligocene-Miocene oceanic crust of the South China Sea along the Manilla Trench (Fig.3.1.3.1).

To the north-east of Taiwan the Palaeogene oceanic crust of the West Philippine Sea Basin is subducting below the Eurasian Plate along the Ryukyu Trench, resulting in a volcanic arc, located on continental basement, and the Okinawa marginal basin. South of the island the Oligocene-Miocene oceanic crust of the South China Sea is subducting below the Philippine Sea Plate along the Manila Trench. The resulting Luzon Volcanic Arc can be followed northwards to the coastal range of Taiwan (Fig.3.1.3.2) where it is dated as Miocene-Pliocene in age. This Luzon block, trending north-south, collided obliquely with the Chinese margin to produce Taiwan.

The island can be divided in two along the Longitudinal Valley in which a steep fault (50-55 degrees) dipping to the east down to a depth of 50km. can be observed. The eastern part consists of the Coastal Range with extrusive Middle-Late Miocene andesitic arc rocks covered by Pliocene-Early Pleistocene clastic sediments. The Lichi Melange interdigitates in the lower part and comprises a variety of blocks including fragments of an Early Miocene ophiolite. This Coastal Range was folded 50,000 years ago. West of the Longitudinal Valley lie the imbricated and thrusted units of the Chinese continental margin. Here, the western Coastal Plain consists of Pleistocene molasse, foothills of imbricated Late Oligocene to Early Pleistocene cover, while the interior Central Range is composed of a large thrust sheet of Eocene to early Miocene folded sediments, a complex pre-Tertiary unit forming the backbone of the range and a suite of meta-



Schematic map of the present-day tectonic features surrounding Taiwan, with indications of the instantaneous convergence vector of the Philippine Sea plate relative to the Eurasian plate, about 7 cm/yr (from Seno, 1977) and the magnetic anomalies of the South China Sea (from Taylor and Hayes, 1983). 1 = Eurasian continental margin; 2 = fore-arc basins; 3 = Luzon volcanic arc with its active volcanos related to the subduction of the South China Sea along the Manila Trench; 4 = Bicol volcanic arc and the active volcanos related to the subduction of the Philippine Sea plate along the Philippine Trench. PSF—Philippine fault; *NLT*—North Luzon trough; *WLT*—West Luzon through; *NB*—Nanao basin; YR—Yaeyama ridge.

FIGURE 3.1.3.1 Tectonic features of the Taiwan region. From Pelletier and Stephan, 1986

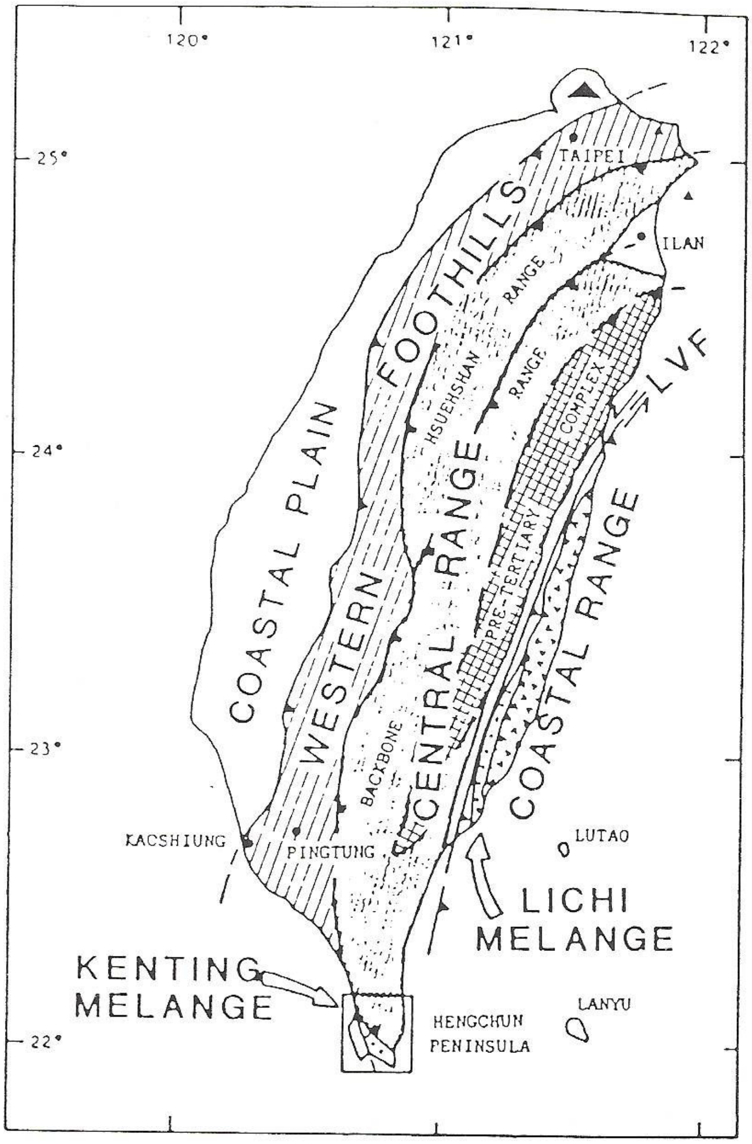
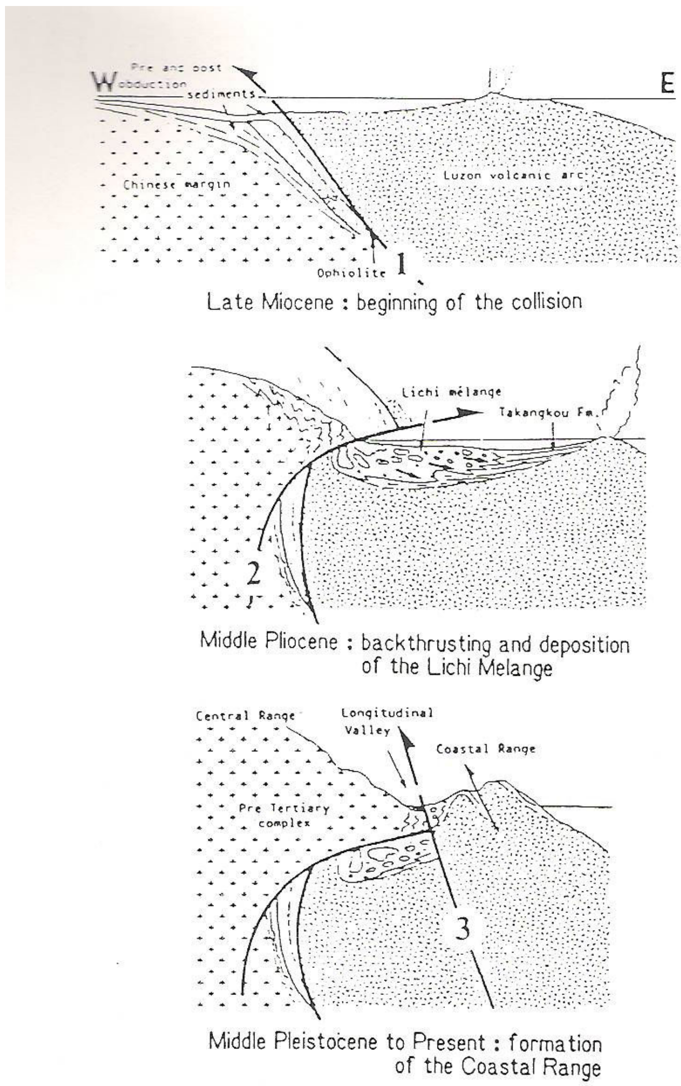


FIGURE 3.1.3.2 Structural framework of Taiwan, from Pelletier and Stephan, 1986. LVF = Longitudinal Valley Fault.

ophiolites. This Central range is unconformably overlain by Eocene quartzites and phyllites followed by Early to early Middle Miocene phyllites.

Pelletier and Stephan(1986) believe that obduction occurred in the Middle Miocene prior to the collision which followed 6-8 m.y. later. They point out that the tectonized Chinese continental margin constitutes the major part of the island and that the volcanic arc, which was deformed in the Quaternary, occupies a small area. The arc was initially thrust a short distance over the margin, which was then thickened by imbrication, leading to a mushroom-shaped structure as the margin thrust back over the arc domain (Fig.3.1.3.3). This back-thrusting induces subsidence of the arc to the east and the development of a new basin which migrates eastwards. Finally, the eastern part of the arc was folded and thrust westward over the margin of the Longitudinal Valley Fault. This plate tectonic evolution is summarised in Fig.3.1.3.4.

The Bouguer anomaly map of Taiwan (Fig.3.1.3.5) shows that steep positive gradients on the east coast reach values of +80mGal and continue to increase offshore. Onshore this 'high' correlates with the outcrop of the obducted volcanic arc. The form of the high is sinuous suggesting a varying thickness of the obducted unit overlying Paleozoic and Mesozoic basement. Anomaly gradients decrease sharply across the Longitudinal Valley Fault reaching -100mGal in the centre of the island. Elsewhere in the centre of the island are other lows of -80 and -50mGal. All are probably due to a thickening of the continental basement by imbrication and folding, and also to thick Plio-Pleistocene sequences of molasse in localised basins. Further west of the central region the anomaly values increase to around 0mGal at the west coast. There are a few localised highs and lows that are probably due to small basins and basement ridges. Some 50km offshore to the west, values on the island of Penghu are around +45mGal. This steady increase in the regional field from the -60mGal of the central area is probably related to the emergence of the Mesozoic basement, as evidenced by shallow basement encountered in exploratory drilling on Penghu Island.



Successive geometry of the suture zone between the Philippine Sea and Eurasia plates during the collision of Taiwan.

Late Miocene: Beginning of the collision between the Luzon volcanic arc (Philippine Sea plate) and the Chinese margin (Eurasia plate). The margin is constituted by a pre-Tertiary complex (in cross) and a Tertiary sedimentary cover including a slice of previously obducted Oligo-Miocene ophiolite. At the beginning of the collision the margin is folded, imbricated and thrust towards the west (see Fig. 7). Only one thrust fault (thrust 1) is drawn on the figure; it symbolizes the suture.

Middle Pliocene: The collision process is going on; the deformed margin is now backthrust towards the east over the Luzon arc (thrust 2). At the front of the thrust, blocks of various sizes and types (Miocene oceanic crust, China margin clastics and Luzon arc andesites) fall down and are incorporated in a chaotic formation which is progressively squeezed and pushed forward. This tectosedimentary complex, i.e. the Lichi mélange, slides towards the newly created eastern trough where it is finally intercalated in the Pliocene clastic sedimentation (= Takangkou Fm.).

Middle Pleistocene to Present: This cross section shows the present-day structure of the suture zone. The eastern part of the arc and its sedimentary cover are folded and thrust over the pre-Tertiary rocks of the margin along the Longitudinal Valley fault (thrust 3). Note that in this interpretation a large part of the Lichi mélange, the Luzon arc and Oligo-Miocene ophiolite are burrowed below the eastern part of the pre-Tertiary complex.

FIGURE 3.1.3.3 Geometry of the suture zone during the collision of Taiwan. From Pelletier and Stephan, 1986.

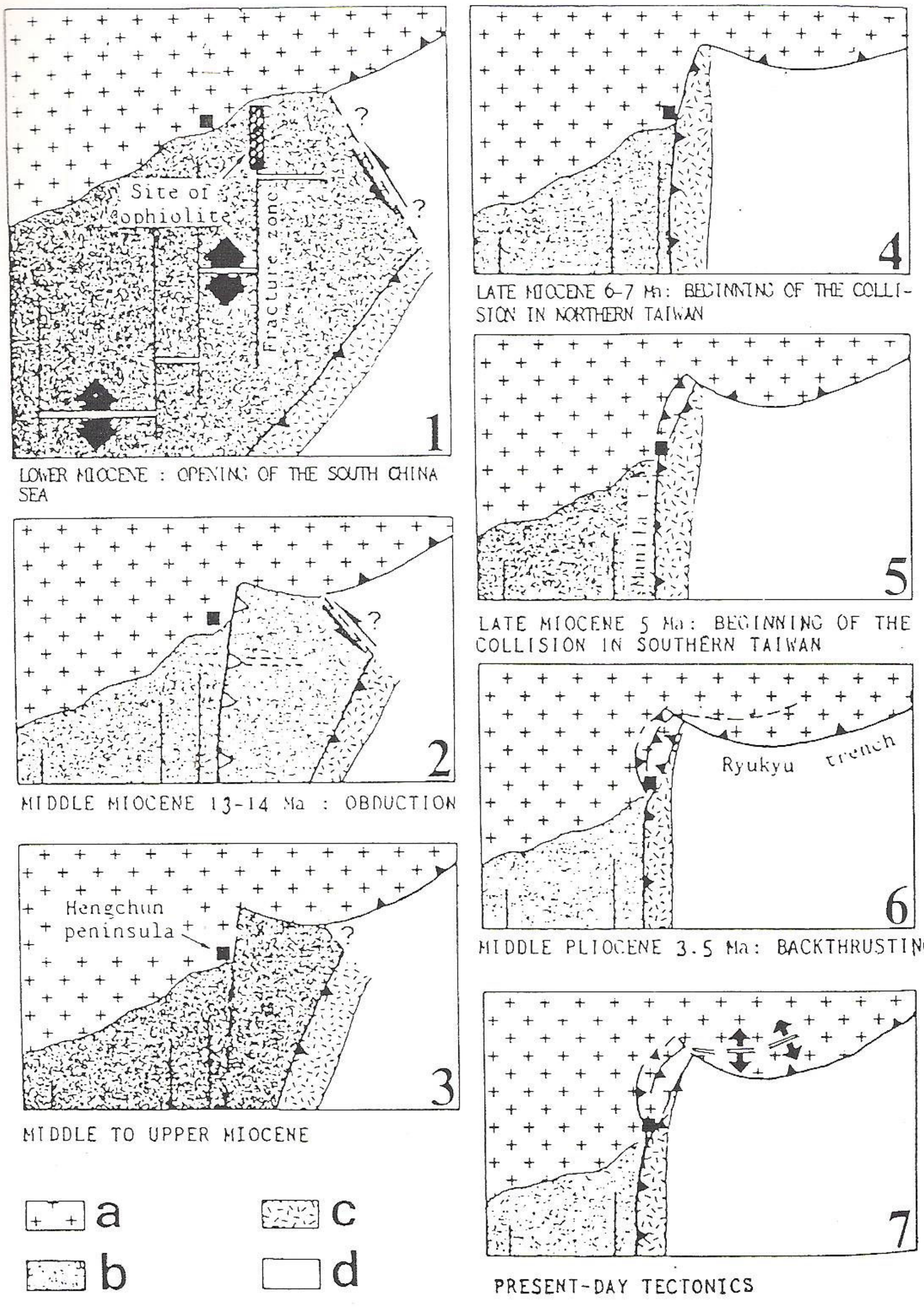


FIGURE 3.1.3.4 Platetectonic evolution of the Taiwan/Luzon area. a=Chinese margin; b=South China Sea oceanic crust; c=Luzon volcanic arc; d=West Philippine Sea basin. From Pelletier and Stephan, 1986.

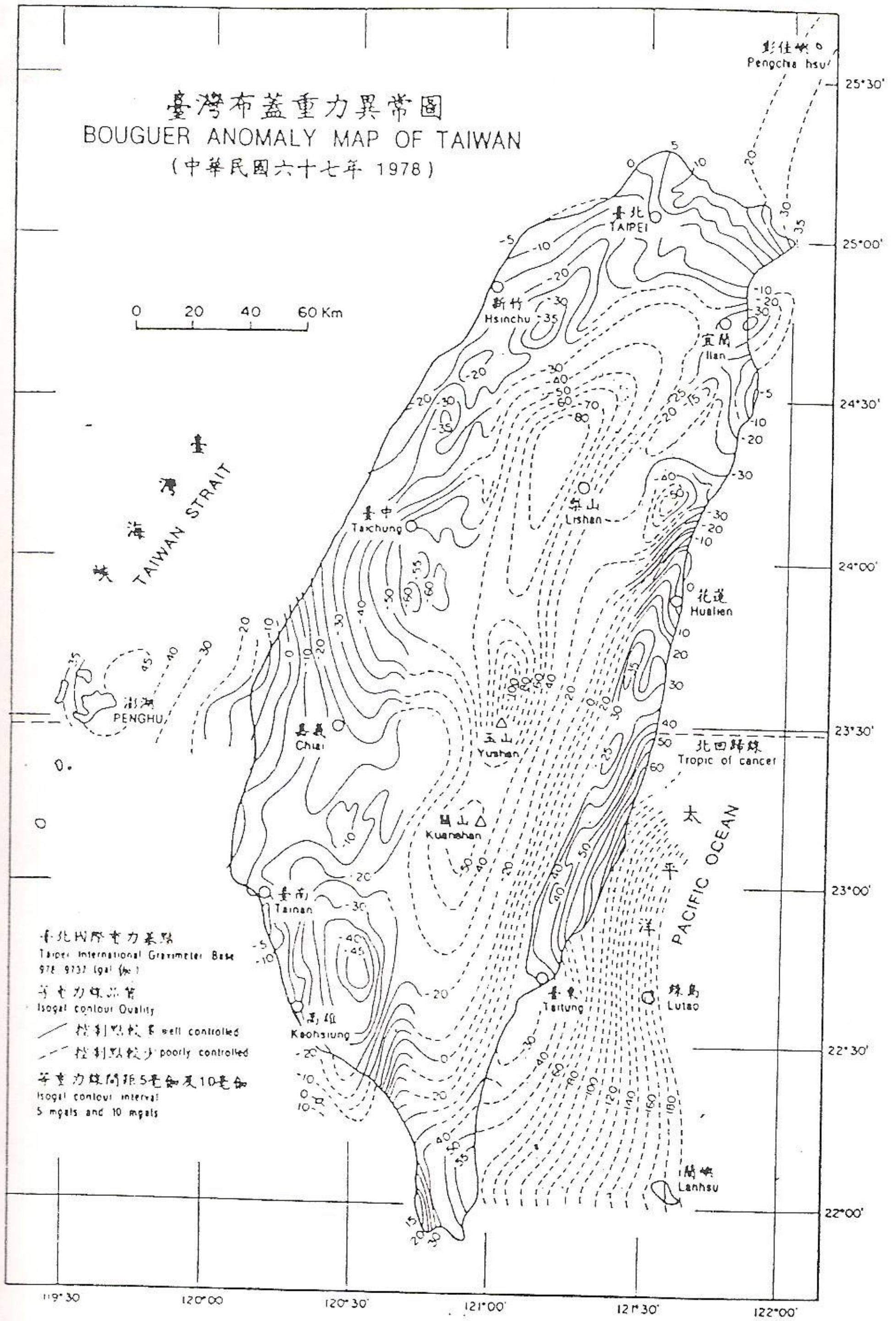


FIGURE 3.1.3.5 Bouguer anomaly map of Taiwan. Compiled by the Mining Research and Service Organization and Chinese Petroleum Corporation.

3.1.4 THE QUESTION OF OPHIOLITES IN THE SOUTHERN BANDA ARC

Most of the ophiolite examples discussed above are in areas where large sheets of oceanic/volcanic arc crustal material have been emplaced onto the continental side of a convergent margin. Timor is undoubtedly such a margin but large extensive ophiolite sheets due to the Miocene/Pliocene collision are not seen. The only area in Timor where volcanic arc material rests upon continental, and has not been dismembered by tectonism, is the Ocussi region of West Timor. Here the Manamas Volocanics and Ultra-basic Formations do form a large body at the edge of the continental margin. However, the form of these rocks suggests an emplacement due to volcanic arc overthrusting and not to thrusting of ophiolite sheets. This distinction may be partially semantic but is meant to imply that these units are not likely to form extensive sheets. However, the stress applied to both overthrust and obducted sheets must be directed southward.

Elsewhere in northern and central Timor, occur thrust sheets of sedimentary allochthonous units associated with ultra-basics and serpentinite. These are not ophiolitic and are probably the result of tectonic mixing of volcanic arc and Australian margin units in the initial phases of the Mio/Pliocene collision.

The results of the gravity modelling of Timor (Chapter 1.4) shows the requirement for an upturned segment of the lower crust and mantle of the volcanic arc immediately off-shore of northern Timor. This segment may have caused the late stage on-shore thrusting of the Manamas Volcanics etc. of West Timor. In the future this segment may form an ophiolite, however, the present rapid up-lift of the continental margin suggests that ophiolite emplacement is unlikely. A similar upturned segment of the arc is modelled adjacent to the continental margin in the Tanimbar region (section 2.2.3.2). Why the two modelled segments were not emplaced as ophiolite sheets during collision was probably due to the oblique nature of the arc-continent collision. A considerable amount of oblique strike-slip would decrease the orthogonal stress at the convergent margin, which may inhibit the emplacement of large sheets, and possibly result in the present configuration.

CHAPTER 3.2

THE DEVELOPMENT OF THE BANDA ARCS

3.2.1 RIGHT-LATERAL VERSES LEFT-LATERAL GEOMETRIES

In Chapter 1.4 the development of the Timor region was examined and concluded that all of the necessary convergence of the Australian Plate could be accommodated within the area. This was primarily accomplished by the subduction of 50-60km of continental crust followed by the northward horizontal movement of the Australian Plate. This implies that much of the shortening occurred between the volcanic inner arc and the Australian para-autochthon. An important part of this shortening was inferred to have taken place by eastward translation of the islands of Kisar, Leti and Sermata from northern Timor, in a right-lateral system, shortly after the initial collision of the Australian continental margin. However, the Australian-Indian Ocean Plate is reportedly moving NNE with respect to the Eurasian Plate (c.f.Minster and Jordan,1978), while to the north, the Pacific Plate is moving westward, thereby creating an overall left-lateral geometry in the Banda Sea region.

This left-lateral geometry does not preclude the eastward translation of Kisar etc if East Timor was a promontory on the leading edge of the Australian Continental margin. In this case East Timor would collide obliquely with the subduction zone, prior to West Timor, resulting in a localised anticlockwise rotation of the left-lateral geometry. This would allow the eastward translation of Kisar etc along antithetic strike-slip systems. As convergence and collision proceeded, and the East Timor promontory was tectonically eroded and shortened, the left-lateral geometry would rotate clockwise within the region, giving rise to the observed 20-30 km clockwise rotation of Kisar etc.

However, a localised right-lateral system can be inferred if the Southeast Asia Plate was moving eastward at 60km/m.y. relative to the Eurasian Plate (Johnston and Bowin 1981).

Terman (1977) suggests that the Southeast Asia Plate is rotating anticlockwise relative to Eurasia about a pole located a few degrees east of Taiwan. Additionally, Molnar and Tapponier (1975) conclude that the India/China continental collision is causing Southeast Asia to move along transcurrent faults in a southeasterly direction relative to Eurasia. This right-lateral geometry would allow the eastward translation of Kisar etc along synthetic fault systems, followed by a body rotation of Kisar etc after the initial collision.

Both left and right lateral geometries would produce the observed features within the Timor region. Swapping between the two systems turns synthetic into antithetic faults, but the relative movement of blocks remains the same. Therefore, it would appear that there is no unequivocal evidence in favour of either a left or right lateral geometry within the area. Only a greater knowledge of the absolute, and consequently relative plate motions, will help decide this matter.

In conclusion, even if the inferred promontory of East Timor did initially collide within a right-lateral system, the resulting faults would remain active in a left-lateral geometry and would also have the same sense of movement. It is generally agreed that the Banda Sea region is now dominated by a left-lateral stress regime created by the NNE movement of the Australian-Indian Ocean Plate and the westward movement of the Pacific Plate. It is therefore, possible that an earlier right-lateral configuration in the Timor region has been over-printed by the Banda Sea left-lateral geometry.

3.2.2 THE FORM OF THE SUBDUCTED AUSTRALIAN PLATE

It is commonly agreed that lithosphere of the Australian - Indian Ocean Plate is being subducted beneath the Banda Arcs from Bali to Banda Api (a volcanic island south of Seram). Hamilton (1979) came to the conclusion that the subducted lithosphere roughly mirrored the curvature of the Banda Arcs to form a west-plunging synform, with subduction northward at the Timor Trough, westward at the Aru Trough and southward from the Seram Trough. However, Cardwell and Isaacs (1978) observed that the seismic zone dipped northward from the Timor Trough to a depth of 600km but does not extend back up to the Seram Trough. They concluded that the simplest subduction model is one in which a single plate of lithosphere is subducted between the Sunda/Banda Arcs along the Java - Timor - Tanimbar - Aru trough system. This plate is continuously contorted along its length, from the surface to 600km, as a result of subduction at a curved trench. Maximum rotation of the plate occurs at approximately 129° E, just to the west of the Tanimbar Islands, where the arc has its greatest curvature. This causes the subducting plate to steepen considerably. The definable subducting plate terminates at the northern end of the Weber Basin. In the Seram region the south-facing island arc system lies to the south of the Seram trough from which a poorly defined seismic zone dips southward to a depth of approximately 100km. Additionally, McCaffrey (1988) after examining centroid depths, seismic moments and fault plane solutions states that the Australian Plate can not subduct simultaneously beneath Timor and Seram. It is probable that the Bird's Head of Irian Jaya is separated from the main body of New Guinea, which is itself still in contact with that part of the Australian Plate that has not yet been deformed by the subduction processes at the Banda Arcs. Simply, the Bird's Head has detached from New Guinea along a line drawn along the south-east side of the Aru Trough, north-eastward along the eastern margin of Sarera Bay. This may have been brought about by the westward convergence of the Pacific Plate, causing the westward rotation of the Bird's Head with resultant subduction southward at the Seram Trough.

Locally within the Timor region, McCaffrey et al (1985) describe the results of a microearthquake survey. They note that near Pantar, a volcanic arc island to the NW of Timor, a 70 to 200km deep seismic zone suggests that the north dipping slab strikes N65° E, paralleling Timor and the Timor Trough rather than the overall E-W trend of the convergent margin. This is a 25 degree anticlockwise bend in the subducting slab which they infer was subducted approximately 4m.y. ago at the time the Australian continent collided with the

Sunda Arc. They suggest that the bend in the slab was brought about by the subduction of buoyant Australian continental crust. This conclusion is in agreement with plate reconstructions and modelling used in this thesis. Fault plane solutions indicate a detachment within the subducting slab at 50 to 100 km parallel to the north coast of Timor. This proposed detachment is likely to occur at a major lithological boundary within the subducting slab. The location of such a boundary is consistent with gravity model two of Timor used in this study where 50 to 60km of continental crust is inferred to have been subducted (Fig 1.4.1.3).

3.2.3 THE FORM OF THE BANDA ARC.

The Timor gravity modelling and resulting conclusions described in Chapter 1.4 were based on the stated premise that all of the required convergence has been taken up within the Timor region. However, to conclude with such a parochial view is unwise.

In the preceding sections of this chapter it was shown that subduction is, or was until recently, occurring around the Banda Arc from Timor to Seram, but that there are probably two plates involved. One from the south subducting northward from Timor to just north of the Kai Islands, and the second subducting southward under Seram. Additionally, the Australian Plate is moving NNE at 7 to 7.5cm/yr. These two features, together with the probable shape of the pre-collisional Australian continental margin, are the dominant factors that control the form of the present-day Banda Arc.

An indication of the earlier form of the Australian margin is given by the extent of tectonism and the size and elevation of the islands around the Outer Arc. Timor and Seram are the largest, most tectonised and most elevated of the Outer Arc islands. They are also at opposing ends of the Banda Arc and display a reversed polarity in tectonic and gravity features. Between these two are the smaller, less tectonised, less elevated islands of the Outer Arc (e.g. Kai, Tanimbar, Babar, etc.). It is probable that the energy dissipated in Timor and

Seram was the result of a greater collision event than elsewhere. Each of these island areas can be subdivided into a number of smaller crustal blocks, each displaying differing tectonic histories related to their varying strain regimes but with similar stratigraphies.

Considering Timor alone, the cause of the collision may be due to: 1) Timor being a promontory or plateau at the leading edge of the Australian continental margin; 2) the Timor region is anomalous due to the presence of a large (later to be allochthonous) sedimentary or volcanic margin edifice; 3) the excessive stress applied to the Timor region by the eastward movement of the Southeast Asia Plate, resulting in NNW-SSE relative convergence. None of these possibilities can presently be discounted, and all three could have been operating within the Timor region. A simple combination of Timor as a large sedimentary or volcanic margin forming a promontory or plateau is supported by the stratigraphy and the gravity modelling used in this study. Even within the Timor region there is a differentiation in the behaviour of different crustal blocks. For example, East Timor exhibits greater tectonism, higher elevations and has moved northward relative to West Timor. Even at a more local level there is evident variation in the form and composition of individual allochthonous blocks. Therefore, it seems probable that the Timor region prior to collision was a promontory, or plateau, consisting of sedimentary and volcanic units. The presence of this anomalous margin is probably related to the Pre and Syn-Jurassic break-up of the Australian Shelf (c.f. section 1.4.6).

If the Timor region was a promontory then the area between Timor and the eastern margin of the Tanimbar Islands may have been an embayment on the continental margin, and this feature is in part responsible for the lack of large, highly tectonised and elevated islands. An additional dampening factor may have been the presence of the northern margin of the Malita-Calder Graben. The less dense and less competent sediments of the graben, together with the possible lack of a leading edge ridge, would inhibit the formation of a large Outer Arc edifice.

Assuming that the relative movement of the Indo-Australian Plate is approximately N20^{0}E and that this has been so for the last 4m.y., and that the pre-collision Banda volcanic arc followed the trend of the Java volcanic arc, then it can be assumed that a NE transform system existed from the eastern end of the Banda subduction zone to the Irian Jaya convergent margin. Bowin et al (1980) suggest that the former volcanic arc lies along an arc exposed at Dai Island and continues as a buried feature beneath the outer margin of the Weber Trough and then northward to the extinct volcanoes at Ambon Island. However, this old arc is due to the subduction of a slab south-west under Seram and the slab subducting northward under the South Banda Sea. Therefore, it is possible that the former volcanic arc is not continuous around the Banda Arc, which would allow the presence of a transform system.

If two slabs are being subducted around the Banda Arc then it must be explained how this can be achieved if the Indo-Australian Plate is moving NNE. The northern slab subducting SW under Seram can be explained as the result of the convergence of the Pacific Plate upon Irian Jaya. In this case Seram, prior to the collision with the old volcanic arc, was part of the Irian Jaya block (Bird's Head) which was separating from the main body of New Guinea and being pushed and rotated westward due to the convergence of the Pacific Plate. At the time of collision Seram experienced a similar development to Timor, meaning that a former subduction zone south of Seram is now a suture which separates Seram from the largely volcanic, Ambon Island. Following suturing the subduction decollement stepped successively northward, enabling the formation of the present-day Seram Trough, beneath which Australian continental lithosphere of the Irian Jaya block is slowly being subducted. The northern subducting slab is effectively uninvolved with the subduction and collision processes occurring in the southern Banda Arc and the effect of the NNE movement of the Australian Plate is at a minimum.

Consideration of the southern slab is problematical as it originates from a NNE moving plate. If the slab was laterally unconstrained in the mantle then curvature would not occur. As curvature has been brought about by an anticlockwise rotation then the New Guinea continental block is probably responsible. However, for this continental block to apply the necessary force to the subducting slab, and the upper crustal units creating the curvature of the Banda Arcs, necessitates New Guniea having moved NNE at a slower rate than the rest of the Australian Plate. This implies that nearly all of the convergence of the New Guinea block upon the westward moving Pacific Plate, may have been accommodated by strike-slip attenuation and crustal shortening within the New Guinea region. Abers and McCaffrey (1988) calculate that deformation of the New Guinea Highlands may account for 5 to 20% of the total convergence between the Pacific and Australian Plates in New Guinea. The translation and rotation of the Irian Jaya blocks may also account for much of the convergence in the north of New Guinea. The presence of the south-western margin of the New Guinea continental block to the NE, has probably caused the subduction zone and slab to be rotated anticlockwise. Simply, the curvature of the northerly subducting Australian slab and the Banda Arcs has been caused by the NNE-SSW pincer convergence of the Irian Jaya block from the north, the NNE convergence of the Australian continental margin from Timor to Tanimbar and the presence of the New Guinea continental block.

As convergence of the Australian Plate continued after the curvature of the slab and Banda Arcs the NNE-SSW pincer convergence led to ESE-WNW extension of the Banda Sea region. The majority of the extension is constrained to occur in eastern Indonesia in the area of the Weber and Aru Troughs (section 2.2.5) by the NNE convergence of the Australian Plate and the approximately south-westward movement of the Irian Jaya blocks. However, the zone of extension is migrating westward around the Banda Arc to Timor where recent extensional activity is seen in the Rama12 seismic lines (Chapter 1.3).

Complex interplay of the main converging units upon the eastern Indonesian region resulted in considerable strike-slip activity and rotation of crustal blocks (e.g. the Kai Islands). Subsequently, and after final suturing in Timor and Seram, an extensional phase became dominant which has overprinted the earlier compressional tectonics. The Tanimbar crustal block is still involved in localised compressional tectonism due to its position at the major inflection of the Banda Arc.

Examination of the gravity, magnetic, bathometric and seismic data suggests that the Weber Trough extension is at a maximum on a line WSW-ESE opposite the Kai Islands block. The crescent shape of the trough extends northward to Seram, while to the south the geophysical data indicates that the extensional crescent continues to a line drawn NNE-SSW joining Damar with the Leti Island group. This line is observed on the lithotectonic map (Fig.1.3.3.2) as a major transform separating the old volcanic arc of Wetar and Romang from the present-day inner arc of Damar and Teung etc. East of this transform considerable extension has occurred, while to the west in the Timor region extension is less pronounced. However, as the Australian Plate and Irian Jaya continue to stress the Banda Sea region the Timor area may undergo further extension.

CHAPTER 3.3

GEOPHYSICAL LIMITS AND CONSTRAINTS ON THE STRUCTURE OF THE BANDA ARC

3.3.1 Introduction

This thesis has attempted to produce crustal models of Eastern Indonesia based on geophysical data combined with the known geology of the region. In most parts of the region both datasets are only at the reconnaissance level, hence, more detailed geophysical surveys and geological mapping in the future may give rise to more realistic models. However, there are a number of geophysically defined features resulting from the present study that will constrain interpretive models. Conversely, there are limits that should be applied to the gravity data used in this survey. Both the constraints and limits will be discussed in the sections below.

3.3.2 The Timor Bouguer Anomaly Profile

Bouguer anomaly profiles across the Outer Arc from Timor to Tanimbar have a similar form, with values of approximately +50mGal over the Australian Shelf decreasing to -50mGal north of the Timor - Tanimbar Trough before rising steeply northward to the northern margin of the Outer Arc, where values commonly reach +180 to +220mGal (Fig. 1.4.1.1 and rear pocket). The Bouguer anomaly values over the Australian Shelf are typical of continental crust of approximately standard thickness overlain by a shallow sea.

Over the Timor Trough and south of Timor the gravity data reflects the form of crustal units on seismic images with Australian continental units dipping northward. The -50mGal low is not situated over the Timor Trough but north of this bathymetric feature. The gravity data is explained by a thickening of the crust to between 40 and 45km (models two and one respectively, rear pocket) and by increasing the volume of the near surface units in a manner consistent with the imbrication of continental units. On gravitational grounds alone it is not possible to differentiate between previous models depicting the Timor Trough as part of a forearc accretionary prism or as a foredeep. In both types of model a calculated gravity anomaly could readily be produced to match the observed.

Examination of the Bouguer anomaly field over southern and central Timor possibly supports geological mapping evidence that in some localities the allochthonous Australian margin units form nappes overlying the para-autochthon (see section 1.3.1). A typical example is the nappe comprised largely of Lolotoi Complex rocks situated near the village of Lolotoi in East Timor (Fig.1.3.1.2). Anomaly values are raised some 10mGal above the background level, a level of increase that, given the high density attributed to the Lolotoi, can best be modelled as a nappe. Specifically, a density contrast of approximately 0.2g/cc between the Lolotoi and para-autochthon gives a thickness for the nappe of approximately 2km. To argue on gravitational grounds that this is not a nappe would require that the dense surface rocks rest upon a basement with a much lower density. There are other areas in Timor where nappes of allochthonous material possibly overlie the para-autochthon (see Chapters 1.3 and 1.4).

From mid-Timor northward the Bouguer anomaly profile continues to steepen positively, finally reaching values of +180 to +200 mGal just off the north coast. The high values and steep gradients are possibly due to two features. The first, and least significant, is the required increase in the densities of the crustal units under the northern half of Timor (see model one and two, rear pocket). Significantly, the increase in mass in the upper 20km does not require the densities of the units in this region to exceed continental crustal values, that is, the Australian Continental crust extends as far as, and in most places beyond, the north coast of Timor (Introductory Figure 3 and Fig. 1.3.3.2 and below). However, densities that could be assigned to units below 20km lead to ambiguity in the provenance of the rock units. Namely, these units could be either of arc or continental affinity (see the discussion in section 1.4.3). The second feature contributing to the high values and steep gradients is the presence of dense material, close to the surface, north of Timor where Bouger anomaly values peak (see Fig 1.4.1.1 and profiles, rear pocket). The form of the Bouguer anomaly peaks requires the presence of a dense body (approx. 3.1g/cc) virtually at the sea-bed and extending to sub-crustal depths. The density and form of the body are probably best modelled as upthrust mantle of the arc. Therefore, the southern edge of the body marks the collision/suture zone of the arc-continental collision. Longitudinally the body appears to extend the complete length of Timor except in the region south of the Atauro strike-slip system, where the collision/suture zone has possibly been disrupted by the formation of the graben/ridge complex adjacent to Atauro island. Elsewhere the gravity anomaly field indicates that the collision/suture zone is displaced by left-lateral faults cutting across the Timor region (see Introductory Figure 3 and Fig. 1.3.3.2 and below).

North of the anomaly peaks the profile decreases to approximatelly +175mGal over the Wetar Strait. Here the anomaly field is virtually flat as far as the Inner Arc to the north. The single-channnel seismic line across the Wetar Straits (Fig.1.3.2.6) shows low density sediments thickening towards the Inner Arc, which to compensate requires a larger mass of denser material at depth adjacent to Wetar. Conversely, to the south in the Wetar Straits, the presence of the upthrust mantle requires a large mass of lower density material at depth. In summary, the south to north sharp decrease in mass at the surface requires a compensating south to north increase in mass at depth to explain the flat anomaly field (see Models 1 and 2, rear pocket).

3.3.3 The Tanimbar Bouguer Anomaly Profile

Over the Tanimbar Islands the Bouguer anomaly profile (Fig. 2.2.3.3.1) essentially represents the negative portion of the Timor anomaly profile. From the +10mGal values over the east coast of Yamdena the profile decreases in steps to approximately -35mGal in the western half of the island, before rising over the 'Inner Islands' to approximately +5mGal. The anomaly values over Yamdena and most of the 'Inner Islands' are consistent with a crust of continental origin, a result that agrees with the known surface geology. However, using the present gravity data the location of the arc-continental collision can not be determined, except that it must lie not far to the northwest of the 'Inner Islands'.

Yamdena consists of low density, Tertiary sediments while the 'Inner Islands' comprise higher density, Palaeozoic and Mesozoic rocks. This density differentiation is confirmed by the gravity data with the steep gradients over and adjacent to the 'Inner Islands' being caused by the sharp density contrasts between the two rock types. The form of the profile in this region indicates a steeply inclined boundary between the Palaeozoic/Mesozoic and Tertiary units.

The topography of the eastern half of Jamdena is characterised by a series of NE-SW ridges, elongated sub-parallel to the long axis of the island and descending in elevation from the east coast towards the centre of the island. The Bouguer anomaly profile decreases in a similar fashion, with two large, eastward negative, steps over the ridge complex. The largest step, and steepest gradient, is situated over the east coast (Fig. 2.2.3.3.1). Seaward of this step the form of the profile is not known. However, relatively dense material must be approaching the surface at the coast by way of a northwest dipping, relatively steep, density discontinuity. The same is possibly true for the second step in the Bouguer anomaly profile nearer to the centre of the island, although here there is greater ambiguity in the limits of the interpretation based on the gravity data.

3.3.4 Kai Islands Bouguer Anomaly Profile

The Bouger anomaly profile of the Kai Islands (Fig. 2.2.4.2) is the result of dense material of the

Weber Deep to the west, the thick, low density material of Australian affinity making up most of the island group and the dense material of possibly continental origin underlying Kai Besar.

The profile from Tayandu westward over the Weber Deep is broadly similar to the Tanimbar profile, with the 'Inner Islands' in the Kai group represented by Kur, Fadol, Wonin etc. The arc-continental boundary must lie to the west of the 'Inner Islands'. Notable, is the correspondence in the Bouguer anomaly profiles between the 'Inner Islands' of the Kai and Tanimbar groups, with steep, arc-ward positive gradients rising from approximately -10mGal to +10mGal.

Eastward of Kur etc. the anomaly profile decreases to approximetly -25mGal over the Tayandu Islands. Here, the gradient is not steep, indicating little horizontal density contrast in the crustal units. The negative Bouguer anomaly values are indicative of thick continental crust. Eastward of Tayandu the anomaly profile becomes positive with values reaching approximately +40mgal over the west coast of Kai Kecil. This eastward positive and moderate gradient is a reflection of a greater mass under Kai Kecil than under Tayandu. The lack of sharp, local gradients possibly indicates a thinning of low density, near to the surface units eastward from Tayandu. However, there are a number of possibilities which could adequately explain the observed profile. By the west coast of Kai Kecil the very dense mass that underlies Kai Besar is affecting the Bouguer anomaly profile by increasing values and steepening the local gradients. Eastward over Kai Kecil the anomaly profile becomes increasingly steep, with values reaching +90mGal by the east coast.

On Kai Besar anomaly values reach approximately +160mGal. The mass distribution causing these very steep gradients and high values can not at present be more than loosely defined, largely due to a lack of data to the east of Kai Besar. It is the high values and steep gradients in the Bouguer anomaly profile over Kai Besar that are extraordinary in comparison to other profiles in Eastern Indonesia. In common with the rest of this study a possible explanation may have been found in examining all of the available data. Topographically Kai Besar is anomalous in the Kai Islands being high, rugged and with steep slopes elongated sub-parallel to the island, while the bathymetry indicates that the island rises steeply from the surrounding seas. Geologically the island comprises Tertiary sediments of the Australian margin which have generally shallow dips and are displaced by a number of sub-parallel normal faults. Therefore, Kai Besar appears to have risen to the surface along normal faults with little compressional tectonics being recently involved. The gravity requires a deep seated, positive mass anomaly situated under Selat Nerong and Kai Besar, which, when combined with the above features, is possibly explained by raised mantle material (Fig. 2.2.4.2).

3.3.5 Crustal Blocks

The Outer Banda Arc appears to curve as one unit through 180 degrees from Timor to Seram. However, this study has resolved a variety of crustal blocks which have, and will probably continue to, develop largely independently according to local stress variations applied by the convergence of the larger Australian, Eurasian and Pacific plates.

The gravity field across the Timor region shows a sinuosity in anomaly contours which indicates that NE-SW trending left-lateral faults have juxtaposed units of varying densities (Map One, rear pocket, Introductory Figure 3 and Fig. 1.3.3.2). Bathymetric, topographic, Landsat and magnetic data used in this study support the gravity data (see Chapter 1.3).

Using the above geophysical data the Timor region can been subdivided into two large crustal blocks - the West and East Timor Crustal Blocks (Introductory Figure 3). The West Timor Crustal Block starts in the west at the margins of the Savu Basin and extends eastward to the NNE-SSW strike-slip zone situated in the vicinity of Atauro Island. The East Timor Crustal Block extends eastward from the major strike-slip zone to the east of Romang, an extinct Inner Arc island. The eastern block has moved northward approximately 40Km relative to the western block. Of course, it has long been recognised that the volcanic islands in the eastern block are inactive, and have probably been so since the initiation of the relative movement between the blocks, which according to the dating of basalts from the islands was some 3Ma. However, the imaging of recently active volcanic edifices and lava flows on GLORIA side-scan sonar data in the Reung Volcanic Province between the West and East Timor Crustal Blocks, suggests that the two blocks may still be diverging along their shared boundary (Fig.1.3.3.2).

Following surveying on the Tanimbar and Kai Islands described in this thesis, two large crustal blocks, each containing the individual island groups, can possibly be defined. The blocks are separated by a 1500m deep bathymetric trough that strikes NW-SE between the southern margin of the Aru Trough and the eastern margin of the Weber Deep (Introductory Figure 3).

The large crustal blocks described above can be subdivided again into smaller blocks along strike-slip or wrench zones. These local blocks can be distinguished on topographic, geologic and geophysical grounds. For example, in Timor the para-autochthonous and allochthonous regions shown in Figures 1.3.1.3 and 4 are distinguishable by variations in the Bouguer anomaly field which indicates relative movement and differing densities between the blocks. Specifically, nearly every block is bounded on either longitudinal boundary by off-sets in the anomaly field which indicate the left-lateral nature of relative movement.

In Timor the northern boundaries to these local blocks allows the demarcation of the collision/suture zone on gravitational evidence. As discussed in the section on the Timor Bouguer anomaly profile (above), anomaly values reach approximately +180 to 220Mgal and gradients are steeply positive to the north, features that are indicative of mantle of the arc adjacent to Australian Continental material. Hence, Figure 1.3.3.2 and Introductory Figure 3 show that the collision/suture zone lies mostly off-shore of north Timor but can possibly be traced on-shore in the middle of the East Timor Crustal Block.

In the Tanimbar and Kai Crustal Blocks the gravity dataset for this study is not complete towards the Inner Arc and consequently the collision/suture zone here is based on regional compilations of marine data. Nevertheless, high Bouguer values and steep anomaly gradients do exist, indicating that the boundaries between the volcanic arc and Australian Continental material are possibly similar to those in the Timor region. In the Tanimbar Crustal Block off-sets in the Bouguer anomaly field, similar to those seen in Timor have been mapped. These off-sets can also be distinguished in the LandSat images and related to geological and topographic features (Figures 2.2.5.1, 2.2.5.5 and Introductory Figure 3).

Off-sets in the Kai Crustal Block are not seen in the Bouguer anomaly field, nor are they evident in the geology and topography.

3.3.5 Sub-Crustal Limits to Gravity Interpretation

The gravitational inverse-square law means that efforts to differentiate sub-crustal structures are plaqued by ambiguities. Any modelling at these depths relies upon the rigour that can be applied to mass determinations at higher levels, to seismic refraction results, to seismicity data and to information gathered from multi-disciplinary studies to determine the rheology of sub-crustal material.

In the Timor region the leading edge of the subducting plate is constrained by seismicity data which requires that the Benioff Zone dips at approximately 60 degrees. When modelled at this dip the calculated gravity anomalies closely match the observed anomalies over the southern Banda Sea (Bowin, et al,1981). However, the mass distribution in the upper crust of the Banda Sea is not well known and so it must be concluded that the gravity method contributes little to an understanding of sub-crustal form.

In both models One and two (rear pocket) the Australian Continental crust between mid-Timor and the Timor Trough has been thickened below 35km. Gravitational constraints on this feature are not without ambiguity, they being largely dependent on the densities applied to units of the Australian para-autochthon and autochthon. However, to remove the crustal thickening would require a decrease in density of the upper units that may seem unreasonable, given the present understanding of the distribution of geological units within an imbricate and underplated system.

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APPENDIX F. DESCRIPTIONS OF TANIMBAR ISLANDS MUD VOLCANO EJECTA

All the rocks described in this appendix have been gathered from mud volcanoes in the Selat Yamdena region of the Tanimbar Islands and particularly from the mud-volcanic island of Keswui(Fig.2). Because of the similarity of the ejecta clasts throughout the area the samples are not related to their individual mud volcanoes. For the sake of brevity the descriptions are short with only the pertinent diagnostic features mentioned.

SAMPLE 2. Hand specimen.

A heavy, black to yellow/orange rock with concentric iron banding. Iron bands encircle areas of soft, yellow rock made up of rounded and lozenge shaped pieces. The soft areas show evidence of mineral migration from the concentric bands into the centre. The ironstone bands have in places been disrupted by shearing and subsequently been recemented. A concentric banded ironstone. Presumed age - Jurassic.

Thin section.

Most of the section is black in xpl due to the presence of iron oxides. Filaments of iron oxide finger into the soft yellow material which is made of a very fine grained matrix of quartz with small grains of limonite which speckle the matrix.

SAMPLE 9A. Hand specimen.

A whitish yellow, light, fine grained sandstone. Well cemented with no discernable sedimentary structures. Some coarser grained areas may be burrow infills. The rock has light brown speckles in some areas - probably a weathering effect.

Thin section.

Fine grained sandstone with >95% quartz with constituent muscovite, feldspar, chert and chamosite. The majority of quartz grains are euhedral and densely packed, nearly all show pressure solution and suturing of grain boundaries. Most grains have a fresh, rounded appearance with secondary overgrowths. A quartz arenite.

Sample 9B. Hand specimen.

A pink to pale white, moderately heavy, soft,very fine grained rock with calcite veining. The sample has a shell like coating approximately 1mm thick - this material has the same composition as the interior but a little coarser grained. The boundary between the shell and inner is marked by limonite and iron oxides. The whole specimen has straight edges and sharp corners.

Thin section.

Fine grained, micritic, calci-lutite with relict globigerinids and radiolaria. Micrite has replaced much of the primary structures - relict burrows, general bioturbation and some of the larger fossils. Many relict quartz filled radiolara. Presumed age - Miocene.

SAMPLE 10A. Hand specimen.

A fine grained, moderately heavy, hard, laminated and cross-bedded sandstone showing concentric alteration of the interior. The rock has been disrupted and recemented by calcite.

Thin section.

Very fine, angular to sub-rounded quartz grains in a calcite matrix. Muscovite and feldspar lathes plus chamosite forming lamination surfaces. Burrow structures infilled with sparry calcite. Many lithic clasts commonly disrupted by burrows. Most of the muscovite has been broken down to chlorite and clay minerals. Many quartz grains are matrix supported probably due to bioturbation. A fine grained, bioturbated calc-arenite.

SAMPLE 10B. Hand specimen.

A planar laminated, red-grey, medium to coarse grained quartzite with a calcite cement. Weathered surfaces are red with pale white speckles. Graded bedding is evident. Thin section.

Fine grained, angular to sub-rounded quartz grains in a calcite matrix. evidence of some bioturbation. Laminated and graded layers, the upper surfaces being sites of limonite ellipsoidal grains. Within the upper surfaces are bioclastic fragment together with pelloids. Bioclasts include calcareous algae, algal filaments, foraminifera and brachiopods. each laminated band is 1-2mm in thickness and planar possibly indicating high energy. The upper surfaces may represent periods of non-deposition that were colonised and bioturbated. Bioclastic debris is concentrated in these layers.

SAMPLE 10C. Hand specimen.

A very fine grained, soft, light, pink-grey, shattered and subsequently calcite veined chert.

Thin section.

A fine grained chert with considerble quantities of iron oxide. Radiolaria ghost structures and quartz veining. Overall massive appearance with no structures discernable.

SAMPLE 11. Hand specimen.

A coarse grained sorted calc-arenite with large quartz and clay clasts 2-3mm in size. Poorly graded, well consolidated and hard with an outer weathered surface some 2-3mm thick that is highly reactive to HCL.

Thin section.

A variety of clasts and grains in a sparry calcite matrix. The majority of grains are quartz. These are fresh, show no strain and frequently have syntaxial overgrowths. The quartz is well rounded, layered, graded and 0.3-1.0mm in size. There are clasts of strained quartz and chert. Other clasts include micrite masses, coarse grained calcite aggregates, peloidal micrite and micritised shell debris. Bioclasts include bivalve, algal and foram fragments. Opaques largely consist of ellipsoidal limonite occuring individually or as masses and frequently associated with limestone clasts. The matrix is predominantly spar with a little micrite.

SAMPLE 12. Hand specimen.

A massive, dense, heavy, hard, grey, fine grained rock with no discernable structures. Non-reactive to HCL. A quartz arenite.

Thin section.

Graded bedding and burrow structures are evident. Burrows are filled with a matrix of sparry calcite supported quartz. Outside the burrows the quartz grains are 0.05-0.1mm in size, well sorted and rounded. Pressure solution and suturing is evident. Here the matrix is microcrystalline quartz together with clay minerals and chlorite. Layering is picked out by muscovite and chlorite, the muscovite commonly showing alteration to chlorite and clay minerals. A burrowed, mature, strained, litharenite.

SAMPLE 13. Hand specimen.

A very coarse grained limestone. Quartz grains 1-3mm in size together with foraminifera in a calcite matrix. Very poorly sorted, angular to sub-angular grains showing grading.

Thin section.

The quartz allochems are commonly 1-3mm in size, sub-angular, fresh and suspended in a fine sparry matrix. Chert allochems of a similar size make up <10% of the rock. Other allochems consist of micrite, algal fragments, a few peloids, forams and coral.

The forams are probably Nummulites.

SAMPLE 14A. Hand specimen.

A heavy, grey, compact, micaceous, very fine sandstone with cross-bedding and burrows. The burrows are picked out by a darker infill.

Thin section.

The section is laminated but does not show any marked grading. Lamination surfaces are sights of muscovite and quartz grains in a chlorite and clay matrix. Many of the muscovite grains are degrading to chlorite. Elsewhere the very fine quartz grains are sutured together resulting in little pore space. Pore space is generally filled with chlorite and clay. The quartz is well sorted, sub-angular and shows overgrowth textures. Calcite veins cut the rock.

SAMPLE 14B. Hand specimen.

A moderately light, hard, compact, laminated red and grey, micaceous fine sandstone which reacts vigorously to HCL.

Thin section.

Sample 14B is very similar to 14A except that it is a little more coarse.

SAMPLE 15. Hand specimen.

A white, very hard, moderately heavy, very fine grained, compact, nodular rock. A silica/chert nodule.

Thin section.

A dark mass of microcrystalline quartz/chert. Veining is common with the interior of the veins filled with opaque material. The sides of the veins show growth of chalcedony.

SAMPLE 16. Hand specimen.

A pale yellow, soft, moderately dense,non-friable rock which shows considerable veining and shearing. A serpentinite.

Thin section.

Serpentinite criss-crossed by calcite veining.

SAMPLE 18. Hand specimen.

A white-pink, moderately hard, dense, heavy, cros-bedded and laminated, very fine grained limestone with infilled burrows and calcite veining.

Thin section.

The majority of the rock consists of micro-sparite with relict structures of peloidal shape. A few vugs have quartz infill. The pink colour is due to iron mineralisation along veins that also impregnates the micro-crystalline matrix. Other veins are filled with well developed sparry calcite. An almost pure micrite. There is a possibility that this is a rock that has undergone some strain and that the micrite is in fact a recrystallization effect leading to the development of marble.

SAMPLE 19. Hand specimen.

A dense, heavy, grey-yellow, foliated carbonate. There are what seem to be dark shear planes along which material has been mobilised.

Thin section.

A rock comprised almost entirely of sparry calcite with a few opaques. In certain areas the opaque grains are common and reach 1mm in size. The rock can be divided into two sorts of areas. Firstly, the sheared zones which are usually bordered by laminations of opaques and clay minerals. Here the calcite crystals have grown preferrentialy into the shear zone and are probably the result of recrystallization. Elsewhere, where recrystallization has not taken place there are 'rubbled' masses of small calcite crystals. Secondly, the relatively undisturbed areas which are characterised by randomly orientated, moderatlylarge (0.25-0.5mm) crystals.

SAMPLE 20. Hand specimen.

A dense, heavy, striated and veined, white rock. reacts to HCL. The rock can be divided into two areas. One shows veined blocks of fine grained, pink, calcite, the other, a white crystalline mass. This is a limestone halfway to becoming a marble - the white crystalline masses are marble. A marmorised limestone.

Thin section.

The marble areas comprise large calcite crystals upto 4mm in size. The pink blocks are made up of very fine grained calcite crystals (secondary micrite?) criss-crossed by calcite veins. Presumbaly, the pink areas mark a transition zone between the former limestone and the marble areas. Some relict structures are evident.

SAMPLE 21. Hand specimen.

A dense, heavy, compact, moderately hard, dark green, very fine grained rock. No sedimentary structures can be seen but there are planes on the surface of the specimen which resemble cleavage planes. There is a common orientaion for these planar surfaces. Thin section.

Silt sized quartz grains in a cloudy amorphous green matrix. The matrix is probably chlorite and gives the rock it's green colour. Muscovite minerals are present and have preferred orientations which vary throughout the rock. There are some linear zones that traverse across the section, while others curve. These zones are characterised by dense masses of quartz crystals and less matrix. This is probably a siltstone that has undergone some strain.

SAMPLE 23A. Hand specimen.

A moderately heavy, hard, pale yellow, laminated and cross-bedded, medium sand grade sandstone with light brown spots on lamination surfaces.

Thin section.

The rock is made up of >95% quartz which shows pressure solution and suturing. There is little matrix but some pore spaces are filled with calcite. Other pore spaces have small, rounded grains of opaque iron oxide. The iron oxide grains also occur on lamination surfaces. Muscovite mica and feldspar occur in small quantities.

SAMPLE 23C. Hand specimen.

A grey to pale yellow, compact, medium weight, fine grained rock, criss-crossed by a network of calcite veins.

Thin section.

The fine grained amorphous groundmass is crossed by many calcite veins of varying thicknesses. In PPL these areas are light brown and in XPL virtually opaque with a few small grey crystals. Possibly a volcanic glass/obsidian.

APPENDIX G TANIMBAR AND KEI GRAVITY BASE STATIONS

The Indonesian Base Gravity Network station at Laha Airport, Ambon was used as the tie point to both island groups. Unfortunatley due to re-development at Laha the original station described by Adkins et al. (1978) has been destroyed but a new station was established by GRDC in January and February 1987 (Sardjono, pers. comm; Figure G1). New bases had to be established for both Tanimbar and Kei, and in both cases the airports are undergoing development and no possible station site could be regarded as permanent. Nor could churches or mosques be used as bases since on both island groups development is resulting in the destruction and rebuilding of buildings of this type. Therefore base stations additional to those at the airport were established in hotels, where it is hoped they will have a longer lifespan than at more traditional sites (Figs. G2-3).

Ambon, Laha Airport. Indonesian Base Gravity Network station IKJ PELUD.
Abs. Grav. 978164.80 Mgal (Sardjono, pers. comm.)
Drift rate for period 8 Sept-20 Oct (Tanimbar survey) =3.1968-05Mgal/min
Drift rate for period 22 Oct-4 Nov (Kei survey) = 3.7063-05Mgal/min

Kellybaid Hotel, Saumlaki, Tanimbar Islands. Survey number TAN87 002.
Mean tide and drift corrected meter reading is 1643.717Mgal with a standard deviation of 0.0239Mgal. ISGN71 value 978111.32Mgal.

Mirah Hotel, Tual, Kei Kecil, Kei Islands. Survey number KAI87 000.
Mean tide and drift corrected meter reading is 1666.106Mgal with a standard deviation of 0.0360Mgal. ISGN71 value 978135.97Mgal.

For the Tanimbar Islands there was one former station established by P.Jezek in 1975 on Pulau Ungar, one of the 'inner islands'. An unsuccessful attempt was made to re-occupy this station but it could not be found. It seems possible that the station was marked in soft sandstone below high tide level and has been eroded away. The Bouguer anomaly value of -22.47Mgal is in close agreement with the two stations established by this survey at -20.84 and -21.64Mgal. In Elat on Kei Besar Jezek established two stations - one at the Catholic Church, the other in a Mosque. Both buildings are being destroyed as bulding materials are removed from them to erect a new Church and Mosque elsewhere in Elat. Again the values for this survey are comparable to Jezek's.

COUNTRY	NEAREST CITY	GRAVITY STATION DESCRIPTION
INDONESIA	AMBON	

STATE PROVINCE COUNTY	STATION NAME	STATION NO.
MALUKU	AMBON AIRPORT - LAHA	IKJ PELUD

LATITUDE	LONGITUDE	ELEVATION
3°43.0'S	128°05.0'E	10.1m

POSITION CONTROL	GRAVITY VALUE
INFORMATION FROM INDONESIAN BASE GRAVITY NETWORK	978164.80 mGal

ELEVATION CONTROL	BOUGUER ANOMALY
INFORMATION FROM INDONESIAN BASE GRAVITY NETWORK	

DESCRIPTION

STATION LOCATED ON SOUTHERN SIDE OF AIR TRAFFIC CONTROL TOWER STATION. POSITION BELOW RAISED WALKWAY ON ROAD TARMAC, JUST 10CM NORTH OF A CONCRETE BLOCK MARKED IKJ PELUD

DESCRIBED BY:	DATE
S. J. KAYE	01/88

DIAGRAM

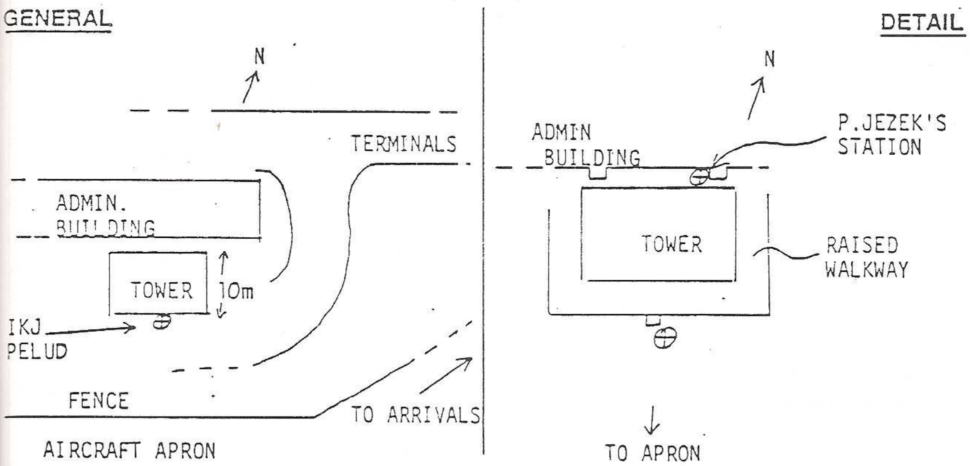

DIAGRAM BY:	DATE
S. J. KAYE	01/88

STATION HISTORY

THE FORMER INDONESIAN BASE GRAVITY NETWORK STATION HAS BEEN DESTROYED.
IKJ PELUD WAS FIRST OCCUPIED IN JANUARY 1987 AND TIED TO THE INDONESIAN NETWORK.
P. JEZEK'S LAHA AIRPORT STATION IS SITUATED NORTH OF THE TOWER ADJACENT TO THE ADMINISTRATION BUILDING.

SOURCE ORGANISATION LONDON UNIVERSITY CONSORTIUM FOR GEOLOGICAL RESEARCH IN SOUTH EAST ASIA AND THE GEOLOGICAL RESEARCH AND DEVELOPMENT CENTRE, BANDUNG, INDONESIA.

FIG. G1

COUNTRY	NEAREST CITY	GRAVITY STATION DESCRIPTION
INDONESIA	TUAL	

STATE / PROVINCE / COUNTY	STATION NAME	STATION NO.
MALUKU KEI ISLANDS	HOTEL MIRAH, TUAL	KEI 000

LATITUDE	LONGITUDE	ELEVATION
5.6402826°S	132.7381592°E	6.0m

POSITION CONTROL	GRAVITY VALUE
LOCAL-TOPOGRAPHIC MAPS HT 1.250,0W	978135.94 mGal

ELEVATION CONTROL	BOUGUER ANOMALY
PAULIN ALTIMETER PLUS VISUAL CHECK	+55.64 mGal

DESCRIPTION

THE STATION IS POSITIONED ON THE FRONT VERANDA OF THE HOTEL, JUST IN FRONT OF THREE STEPS LEADING UP TO THE FRONT DOOR. THE HOTEL IS SITUATED ON THE SIDE OF A HILL OVERLOOKING WESTWARDS TO THE MARKET AND HARBOUR. THE ROAD OUTSIDE THE FRONT OF THE HOTEL LEADS DOWN INTO A ONE-WAY TRAFFIC SYSTEM THAT ENCLOSES THE SHOPPING AND MARKET COMPLEX.

DESCRIBED BY:	DATE
S. J. KAYE	01/88

DIAGRAM

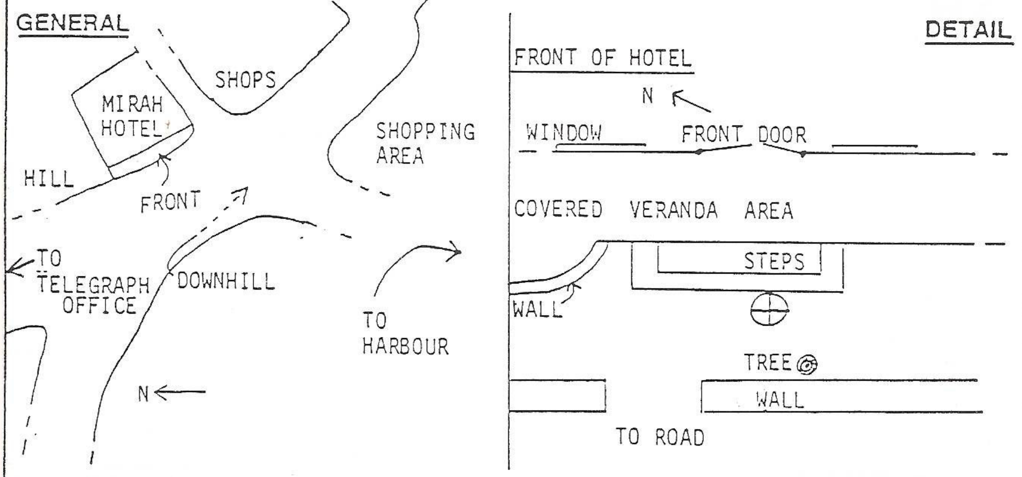

DIAGRAM BY:	DATE
S. J. KAYE	07/88

STATION HISTORY

A NEW STATION ESTABLISHED IN OCTOBER 1987 FOR THE GRAVITY SURVEY OF THE KEI ISLANDS. THIS STATION WAS USED IN PREFERENCE TO ONE AT LANGGUR AIRPORT WHICH WAS BEING DEVELOPED.

SOURCE ORGANISATION LONDON UNIVERSITY CONSORTIUM FOR GEOLOGICAL RESEARCH IN SOUTH EAST ASIA AND THE GEOLOGICAL RESEARCH AND DEVELOPMENT CENTRE, BANDUNG, INDONESIA.

FIG.G2