CHAPTER 3

MIOCENE CORES AND OUTCROPS

3.1 INTRODUCTION

3.1.1 Location and Stratigraphy

The carbonate rocks of the Batu Raja Formation, Early Miocene in age, include the Duma, Nurbani and ZU hydrocarbon reservoirs. The Duma ($5^{o}28'S$, $106^{o}29'E$) and Nurbani ($5^{o}10'S$, $106^{o}05'E$) reservoirs are within the concession area of IIAPCO (Independent Indonesian American Petroleum Company, Division of Diamond Shamrock Corporation) and the ZU reservoir ($5^{o}07'S$, $106^{o}38'E$) within that of ARCO (Atlantic Richfield Company). The location of the three fields is shown in Fig. 30.

All three reservoirs lie within the Cibulaken Group (see Fig. 31 for general stratigraphy of the area). The ZU carbonates span entire period of deposition of the Batu Raja Formation, whilst the Duma carbonates are from the Upper Batu Raja Formation only. The Nurbani buildup grew during the period of deposition of the Upper Batu Raja to Lower Gumai formations. The Duma and Nurbani reservoirs, are both subcommercial, whilst ZU, the largest and most recently discovered of the three fields, is proving commercially productive.

Whilst most detailed work has been carried out on core material, low well density relative to buildup size precludes accurate determination of facies variation by direct visual examination. With the aim of shedding some light on possible lateral facies associations developed in the Batu Raja Formation, studies were made of a number of approximately coeval carbonate buildups which crop out onshore.

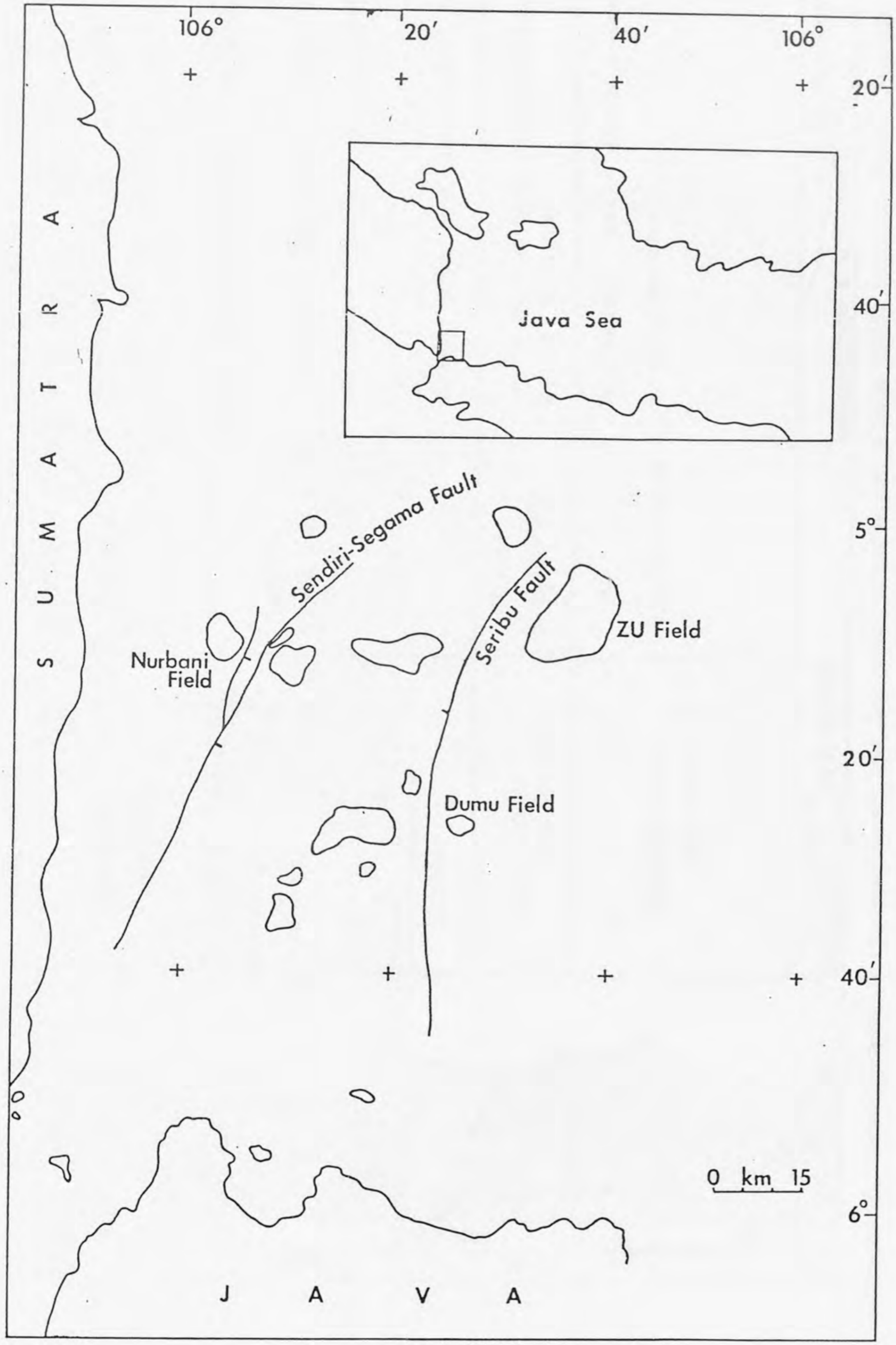


Figure 30 Location of Early Miocene reefal buildups in the southwest Java Sea

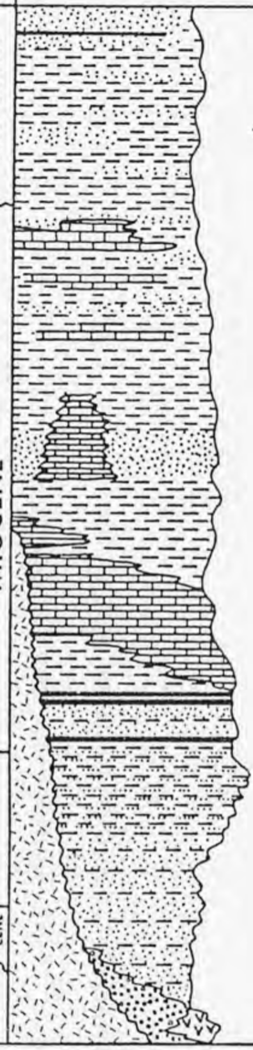
AGE	STRATIGRAPHIC COLOMN	FORMATION & THICKNESS	LITHOLOGICAL GROUP	LITHOLOGICAL DESCRIPTION
Plio-Pleistocene		CISUBAH upto 2400′	CISUBAH	Interbedded claystone sandstone lignite & tuff
MIOCENE Middle		PARIGI upto 150′	UPPER CIBULAKEN	sandy limestone including reefal limestone
		(pre-parigi) (mid-main) AIR BENAKAT (yati′) (krisna) upto 3000′		Glauconitic limestone & sandstone with calcareous carbonaceous claystones
MIOCENE Early		GUMAI		Pelagic shales, minor interbedded limestone
		BATU RAJA upto 1000′	LOWER CIBULAKEN	Biomicritic limestone & carbonaceous claystone Reefal limestone
Oligocene		TALANG AKAR upto 6000′	TALANG AKAR	Interbedded coals shales sandstones & conglomerates
EOCENE / Pre-Tertiary		LAHAT & JATIBARANG / BASEMENT		volcanics & volcanoclastics / metasediment & acid igneous

Figure 31 Stratigraphy of the southwest Java Sea area (after Wight & Loos 1983, internal IIAPCO report, unpub.).

Buildups from the Rajamandala Formation (Fig. 37) were visited at Sukabumi and Bandung, approximately 120 km. south of the oilfields, and the limestones of the Sengkang Basin in South Sulawesi (Late Eocene - Late Miocene, Fig. 39) were examined in order to detect possible variations in approximately contemporaneous carbonates from different areas. The Parigi Limestone Formation (Fig. 37) of late Middle Miocene age, exposed at Cibinong in West Java, was also studied in order to record the changing character of carbonate buildups over time. Fig. 1 shows the locations of the three outcrop areas. Reefal facies and relationships, and those off-reef facies which formed a substrate for reef growth, are discussed in Sections 3.2 - 3.5.

3.1.2 Structure and Tectonism

The Sunda Basinal Area comprises the West Java, Sunda and Biliton Basins (Todd & Pulunggono 1971 internal IIAPCO report, unpub.). The major structural elements are illustrated in Fig. 4, and are;

(i) the fault bounded Sunda Sub-basin

(ii) the Seribu Platform

(iii) the Arjuna Sub-basin

(iv) the Central and Eastern Platforms.

The Sunda Basinal Area is bordered to the west by the South Sumatra Basin and to the south by the Sunda landmass. South and west of these is the active South Java Subduction Zone.

The Tertiary marked an enormous revival of volcanic activity after the relative quiescence of the late Cretaceous (Van Bemmelen 1949). During this episode of mountain building, the marginal back-arc area suffered considerable subsidence and basins were filled with sediment. A north-south block fault system was initiated on a late Cretaceous surface and was most active in the Oligocene and Early Miocene, continuing to a lesser extent through the Middle Miocene (Todd & Pulunggono 1971). A number of isolated oblong basins formed bordering the stable Sundaland and became connected only during the late Middle Miocene transgression.

The three oilfields are located on the flanks of the Sunda Sub-basin, west of the Seribu Platform. The Duma and ZU reservoirs lie on the upthrown eastern side of the NNE-SSW striking Seribu Fault (Fig. 30) on the eastern flank of the graben. The Nurbani field lies on the upthrown western side of the Nurbani Fault - a branch of the Sendiri-Segama Fault which bounds the western side of the graben.

Between the two major faults is the Sunda Trough. Faulting in the area is very complex in detail (Carey 1975), but most of the major faults are subparallel. The Sendiri-Segama Fault cuts all formations upto the Plio-Pleistocene volcanics and was clearly active syndepositionally. Several hundred metres of growth occurred on both the Seribu and the Sendiri-Segama faults, particularly during the period of deposition of the Talang Akar Formation (A. Wight pers. comm. 1983) as a result of the accumulation of thick sediment piles. Renewed growth occurred during the Middle Miocene and Pliocene. Faulting plays a major role both in reefal development and in the migration of hydrocarbons. In the absence of considerable clastic sedimentation, rapid subsidence in areas of growth faulting, permitted thick carbonate sequences to accumulate, for example, the Onny buildup southwest of the Duma buildup.

3.1.3 Patterns of Deposition During the Early Tertiary in the Sunda Basinal Area

The Batu Raja carbonates were deposited upon the Oligocene Talang Akar deltaic sequence which, in turn, is underlain by a granitic and gneissose pre-Tertiary basement. Both basement palaeorelief and the configuration of the Talang Akar sediments influenced the deposition of the younger carbonates.

(a) Basement Controls

The basement was sculpted by fluvial drainage systems which cut deeply-incised valleys in the ZU area during the period prior to the deposition of the Talang Akar Formation. A detailed basement isopach map (ARCO; unavailable for reproduction) drawn up on the basis of seismic transects shows a paleosurface incised by V-shaped valleys. No comparable information could be obtained for the Duma and Nurbani areas.

In the ZU and Duma areas, basement highs influenced the subsequent loci of colonisation by reef-constructing organisms. The east-west elongated ZU High was approximately 130 m. high prior to the deposition of the Talang Akar sediments. It is east-west elongated and has ridges running northwards from it. Approximately 5 km. to the south-east is a second basement high 80 m. in elevation. The Duma High rises to approximately 115 m. No basement topographic highs occur in the Nurbani Field.

(b) Talang Akar Formation

Basement relief was considerable prior to the deposition of the Talang Akar Formation. This Formation largely filled in low-lying areas and is thin or absent on the highs. The regional topography was thus subdued (Robertson Research report unpub.). This unit represents the deposition of subaerially eroded sediments derived from the palaeo-highlands. Initial deposition probably took place in an alluvial fan or fluvial channel environment. The sandstones are clean and composed predominantly of quartz and minor feldspar. Since the overlying carbonates represent a fully marine environment, it is likely that the Talang Akar sediments were reworked partially in a marine littoral environment at the onset of marine transgression.

In the ZU and Duma areas, these sediments flank the underlying basement highs. The 80 m. knoll to the south-east of the main ZU High was completely buried although the High itself continued to exert an influence on sedimentation patterns throughout the Early Miocene (Section 3.2.8). In the Nurbani area, Talang Akar sediments developed a subdued gently-sloping topographic rise which subsequently controlled the site of coral growth.

(c) Batu Raja Formation

During the Oligo-Miocene, the diminished clastic supply and occurrence of carbonate sedimentation and associated reefal growth in many of the foreland basins of Indonesia, suggest that this was a period of tectonic quiescence. A maximum thickness of 330 m. for the Batu Raja Formation is recorded by Burberry (1977) although in the areas studied, the limestones are from 50-120 m. thick.

On a regional scale, the Batu Raja carbonates thicken eastwards and westwards away from the Seribu Platform where the Formation is thin and there are some areas of non-deposition. The rate of subsidence in the Arjuna Sub-basin exceeded that in the Sunda Sub-basin so that larger buildups developed in the former. The limestones thin toward the Arjuna and Sunda troughs. By the onset of deposition of the Batu Raja Formation, the geomorphological terrain was a gently undulating low relief plateau.

The configuration of the carbonate buildups varies in the three areas of study. Figures 32 - 34 illustrate well locations and correlation of stratigraphic units between wells. In the ZU area the carbonates cover all of the high areas. On the crest of the ZU High and on the ridges, the Batu Raja sediments were deposited directly onto basement, but in general the carbonates are underlain by the Talang Akar Formation. The thickest deposits of the Batu Raja Formation in this area lie to the south of the ZU High. North and north-west of the High, the carbonates are thinner and less pure in character. Calcareous shales are encountered within the lower Batu Raja Formation in the north-west, in contrast to the thick massive carbonates present throughout the Formation in the south.

The top of the Batu Raja Formation is marked by the termination of carbonate deposition and a return to a siliclastic regime. This is interpreted as a major regression and is traceable through all of the ZU wells, in contrast to the localised regressions which occurred within the period of deposition of the Batu Raja Formation. Sandstone deposition was extensive and the siliclastic sediments are considered to have been deposited in a prograding subtidal to intertidal environment (Robertson Research report unpub.). Thin glauconitic limestone beds are occasionally interbedded with alternating sandstones and shales indicating an environment with marine influence and rapid changes from current deposition to suspension deposition.

The Batu Raja Formation in the Duma area comprises two units: the Duma Reef Complex and the overlying Duma Carbonate Buildup. These units are overlain by the Duma Clastics which are of fluviatile and deltaic origin, and

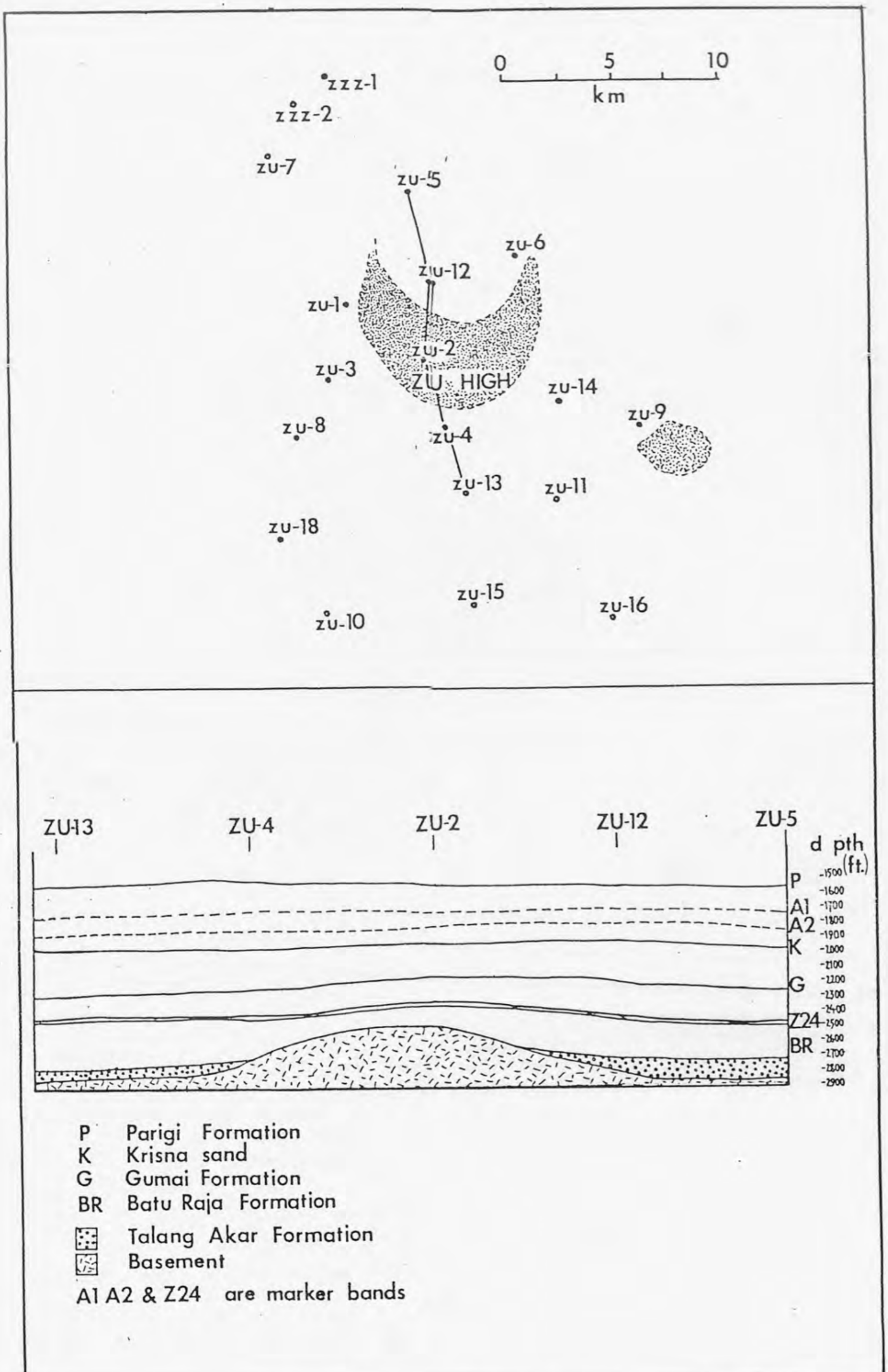


Figure 32 Location of wells and lateral correlation of units in the ZU Field.

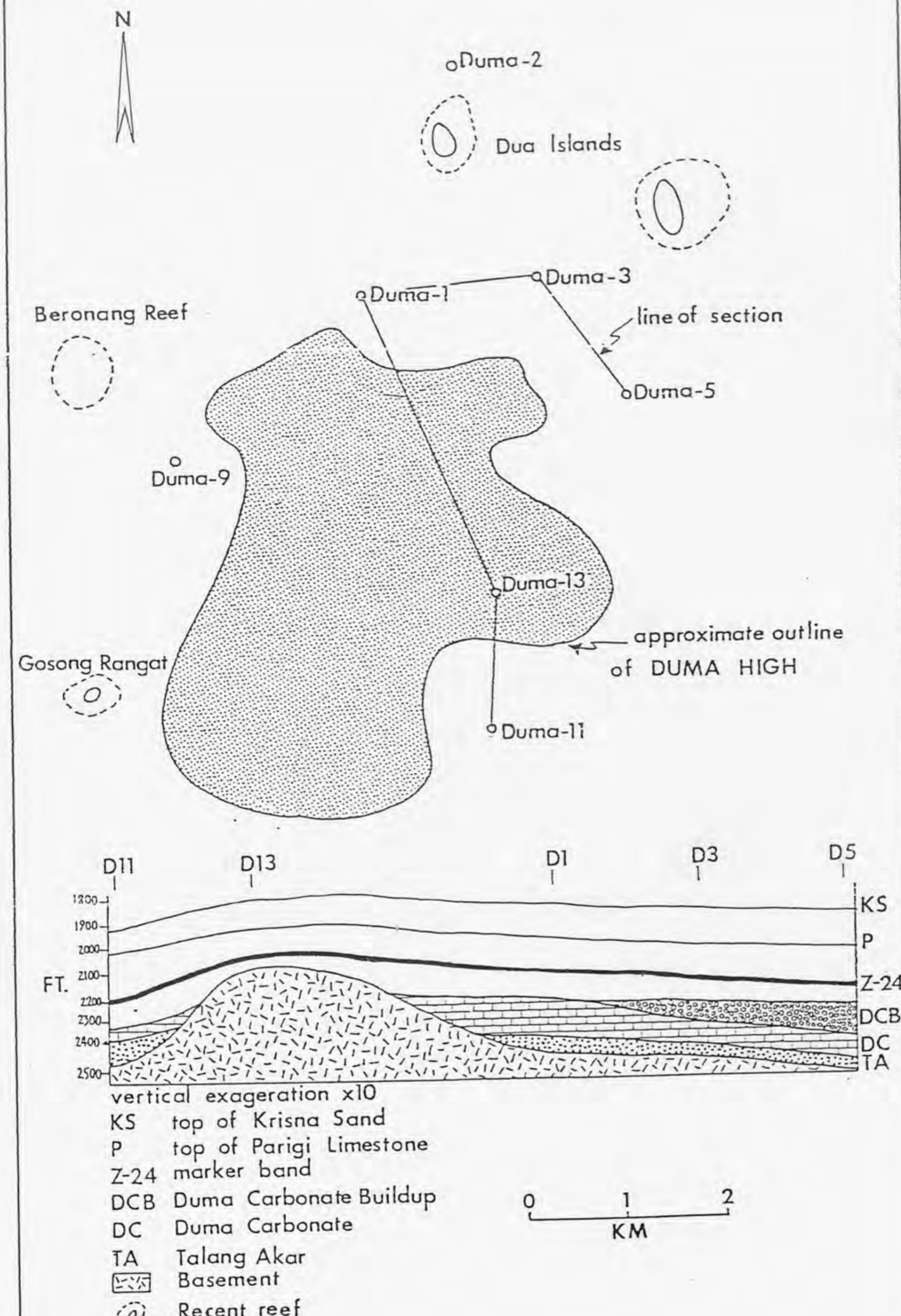


Figure 33 Location of wells and lateral correlation of units in the Duma Field

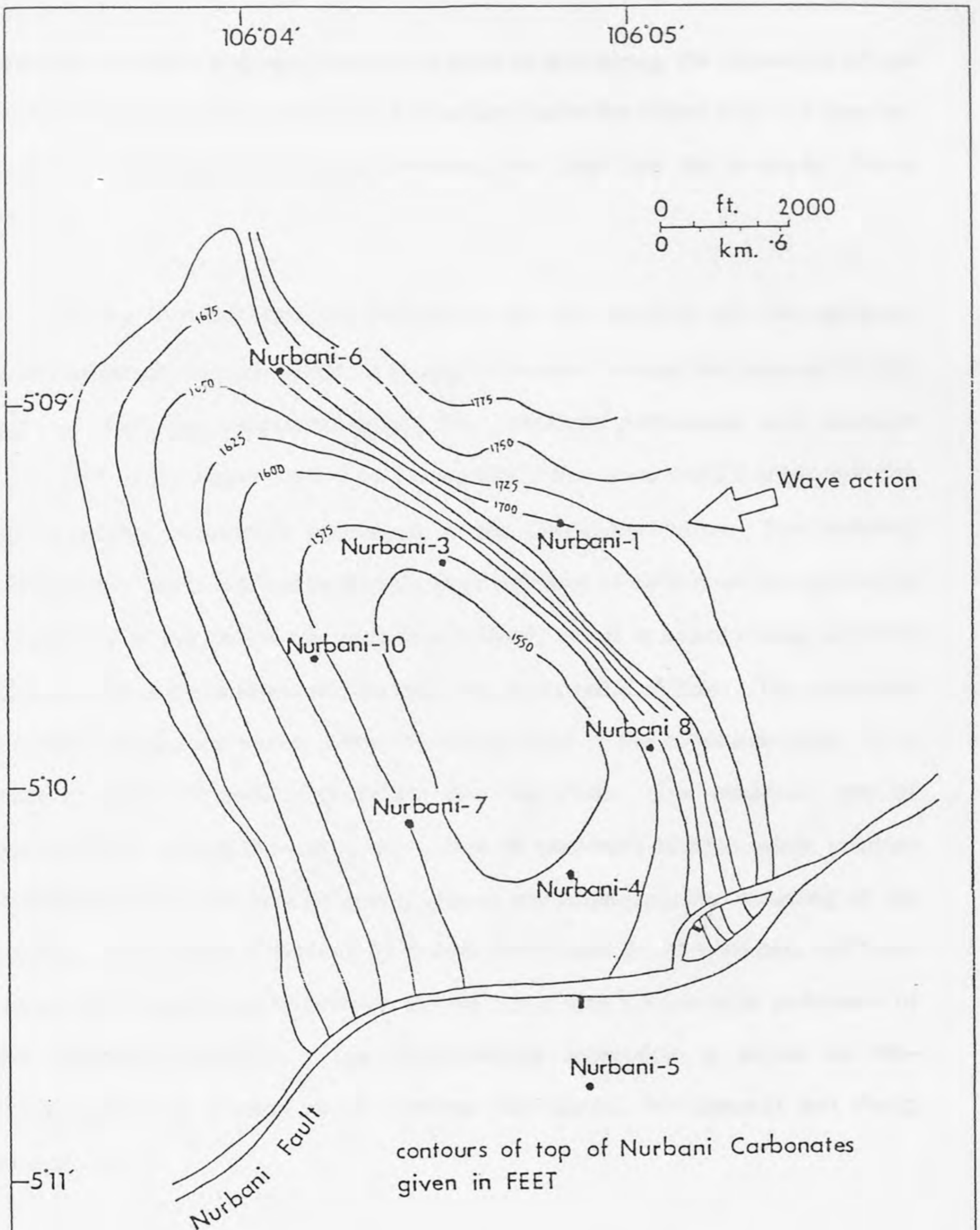


Figure 34 Location of wells in the Nurbani Field.
(after Handoko 1983)

comprise marginal sediments deposited prior to and during the deposition of the Duma Carbonates. The Batu Raja Formation flanks the Duma High but does not cover it; the oldest sediments overlying the High are the youngest Duma Clastics.

In the Nurbani area, the carbonates are also divisible into two units; an older carbonate platform which is of approximately constant thickness of 115 m. and an overlying reefal buildup. The platform carbonates are laterally equivalent to the Upper Batu Raja Formation in the Duma and ZU areas, and the reefal buildup is laterally equivalent to the Gumai Formation. The boundary between the two is marked by a well cemented layer of carbonate skeletal debris referred to as the 'purple marker', that probably acted as a hard stable substrate which corals and shallow water benthic organisms could colonise. The carbonate platform and purple marker were not encountered in the cores examined. Both units covered the underlying Talang Akar anticline. The enhanced rate of transgression toward the end of the period of carbonate sedimentation resulted in contraction of the area of reefal growth and ultimately the drowning of the buildup. The buildup is overlain by basinal limy shales of unknown age, and these shales are unconformably overlain by the tuffaceous continential sediments of the Cisubah Formation. The unconformity represents a period of non-sedimentation or erosion which removed the Gumai, Air Benakat and Parigi formations.

3.2 DEPOSITIONAL FACIES: BATU RAJA FORMATION

Recognition of facies was based predominantly on observation from conventional core logging and petrography of cores from the wells listed in Appendix 2. Detailed core logs are presented in Appendix 4. and intervals over which no core was available for study are indicated. In reconstructing three dimensional facies geometry of the subsurface reservoirs, electric log responses were used to a minor extent in conjunction with core observations. Electric log correlation is an empirical method devised for interpretation of limestone textural types, using realistic determinations of water saturation and conductivity. Compatibility between core logging and electric logs has proved to be highly reliable (W. Stringer pers. comm. 1983). In the Nurbani-3 well, the intervals of missing core were indirectly examined by studying resistivity and water saturation logs which suggested that much of the uncored material is of a fine-grained and porous nature. Correlation between wells aids in improving predictability of the quality and dimensions of the hydrocarbon reservoir.

Integration of all observations has led to the identification of seven primary depositional facies. These are:

(i) Coral intraclastic floatstone-rudstone facies

(ii) Foraminiferal skeletal packstone-wackestone facies

(iii) Algal boundstone facies

(iv) Shelly foraminiferal rudstone facies

(v) Sandy impure grainstone facies

(vi) Sparsely fossiliferous wackestone-lime mudstone facies

(vii) Coal.

The limestones in facies (i)-(v) are generally medium to coarse grained and are principally distinguished from each other by the composition of the skeletal material. The distribution, lithological characteristics and skeletal constituents are described in Section 3.2. Chapter 4 discusses their diagenetic features.

3.2.1 Coral Intraclastic Floatstone-Rudstone

(a) Distribution and Thickness

The coral intraclastic floatstone rudstone facies is volumetrically the most important facies and is encountered in all wells except for Nurbani-10 and ZZZ-2. Electric log responses suggest that the facies may be present in the Nurbani-10 well below the depth of the core base. Elsewhere in the Nurbani Field, the proportion of core within a well represented by this facies, and the thickness of the facies, increases westwards. The facies accounts for 29% and 50% respectively of the recovered core in the Nurbani-3 and Nurbani-4 wells, and 63% and 70% respectively of the recovered core in the Nurbani-5 and Nurbani-6 wells.

In the Duma Field, the facies comprises between 33-65% of the recovered core in the Duma-11, -2 and -9 wells, attaining accumulated thicknesses of between 13' (3.9 m.) and 22' (6.6 m.). The maximum thickness of 27' (8.1 m.) is recorded in the Duma-5 well although this represents only 29% of the total core.

In the ZU Field, the facies was logged in the ZU-3 and ZU-4 wells. It appears also, to correspond to the foliose coral wackestone-packstone facies described by Prior (unpub. ARCO report) in the ZU-1 well although this core was not logged personally. Of the four wells studied, ZU-3 contains the greatest recorded thickness of 26' (7.8 m.) although this represents only 20% of the total recovered core.

(b) Texture

The lithology is unstratified, disorganised in appearance and conglomeratic over most of its thickness (Plates 27, 29). Intraclastic shelly floatstone (Plate 29d-g), coral intraclastic rudstone (Plates 27, 28e) and rare units of foliose coral framestone (Plate 28b-c) and irregularly laminated skeletal wackestone are nonsequentially interbedded. Stacked subhorizontal foliose corals define a crude layering in places, although elsewhere orientation of fragments is inconsistent. Sedimentary structures are virtually absent except for rare discontinuous lamination and streaky bedding. Lamination, where present, is deformed between and wrapped around framework clasts, as a result of pre-lithification compaction (Plate 28b).

The texture varies from matrix-support to framework-support, and a high proportion of micrite is present. In places it is difficult to determine whether corals are detrital or in situ, due to the limited width of the core, although some intervals contain undulose subhorizontal layers 4 to 25 mm. thick of delicate foliose corals, which appear to be in growth position (Plate 28a-c).

The matrix is composed of fine grained muds and admixed coarse sand, and is speckled with abraded bioclastic detritus. Near to the top of the coral intraclastic floatstone-rudstone interval, the matrix is unstratified, commonly blotchy and pelletal, and contains rhodoliths and algal mottling which are absent lower down in the interval. The algal mottling tends to be in subhorizontal layers resulting from algal encrustation of the substrate (Plate 28a). Samples from near the base of the facies are unsorted, commonly burrowed and very rarely exhibit a coarse lamination. Such characteristics suggest that the deposit is largely in situ talus. Skeletal diversity is high, the major components being large angular coral fragments, molluscs and algae. Most corals are detrital and fragments vary from 0.5 - 10 cm. in length. Hydrozoan and scleractinian foliose, branching, massive, ceroid, tabular and meandroid morphologies are present. Skeletal structure is rarely well preserved, although plugging of primary porosity with algal mottled micrite occasionally retains a fine cast of the coral after it is dissolved or neomorphosed (Section 4.5 - 4.6). Fragments are generally angular, lumpy or elongate, and are haphazardly arranged. Foliose coral thickets occur more frequently at high levels of the coral-intraclastic floatstone-rudstone interval. At lower levels the coral assemblage is more diverse, with a higher proportion of scleractinian branched and massive morphologies (Plate 27b-c). Most branched corals are fractured and sub-angular in shape whilst foliose corals are commonly unbroken. Calcareous red algae occur mainly as finely laminated encrustations on skeletal grains. Rhodoliths up to 2 cm. in diameter are rarely present. Both unbroken and comminuted molluscs occur (Plate 29e,36b), and include bivalves and small gastropods. Benthic and planktic foraminifera are subordinate members of the faunal assemblage. The ratio of benthic:planktic foraminifera increases upwards and the mixed foraminiferal assemblage in the upper most levels of the coral intraclastic floatstone rudstone facies is similar to that of the foraminiferal-skeletal packstone-wackestone facies (Section 3.2.2). Fragile spines and thin valves are frequently broken although some of the delicate fossils are unabraded. Elliptical to irregular blue-tinged intraclasts composed of glauconitic packstone (Plate 35f) and lime mud are common and tend to increase in abundance downward (Plate 29a,d,f,g). The intraclasts are irregularly shaped, range in maximum dimension from 12-80 mm. and were probably semi-consolidated at the time of deposition. Scattered fine black grains in the interstitial matrix are interpreted as pyritised faecal pellets. A few intraclasts exhibiting stromatolitic-type layering occur.

Reworking of nodular intraclasts and bioturbation is evident in places. Corals and algally-encrusted clasts are commonly bored by both bivalves and algae (Plate 35a-c) and excavations are filled with fine skeletal packstone or, rarely, occluding brown sparry calcite. The algal bores retain a dark organic lining although the infill is leached out. Shallow rounded borings of indeterminate genesis are common.

3.2.2 Bioclastic Foraminiferal Packstone-Wackestone

(a) Distribution and thickness

The bioclastic foraminiferal packstone-wackestone facies is found in all wells with the exception of Nurbani-10, and in most wells is encountered at shallower levels than the coral-intraclastic floatstone-rudstone facies. Throughout the ZZZ-2 well and in the upper levels of the Duma-5, ZU-4 and Duma-3 wells, the upper part of the facies is interlayered with the sparsely fossiliferous wackestone-lime mudstone facies, and in the Duma-3, -5 and -11 and Nurbani-4 wells, the lower part of the facies is often interlayered with the algal boundstone facies and coral intraclastic floatstone-rudstone facies. Elsewhere the frequency and thickness of bioclastic foraminiferal packstone-wackestone units decreases with depth.

(b) Texture

There are rapid lateral and vertical gradations between packstone and wackestone and the bioclastic content of beds varies from 5-40%. The grain size of the framework constituents is mainly 2-4 mm. although the texture grades to floatstone (Plate 30a,c,d) and rarely rudstone in some intervals which contain abraded scleractinian corals and thin-shelled byssate and boring bivalves upto 30 mm. long. Rare grainstone intervals and lime mud units 8-15 mm. thick alternate with bioclastic wackestone-packstone units.

The colour of the micritic matrix varies from creamy-buff to whitish grey, and contains blue-grey speckled detritus (Plate 30g). The substrate is intermittently laminated (Plate 30c), individual laminae generally being irregular, wispy and discontinuous, and rarely algally-bound. Lenses of unlaminated fine terriginous silt, coarse packstone and nodular masses of lime mud also occur. The wavy to smooth layering, where present, is defined by fine grain size alternations and by concentrations of skeletal grains. In parts of the Duma-3 and -5 wells, anastomosing fine, dark, blue-grey, subhorizontal muddy partings, fine mud drapes and tabular coral fragments emphasize the layering and rapid alternation of grain size (Plate 30c,f).

Apart from intermittent bedding lamination, sedimentary structures are rare. Fining-upward cycles occur in units 15-60 cm. thick, and occasionally low-angle cross-bedding is apparent. In a muddy interval of ZU-1, mud cracks are present. These have been partly filled with lozenge-shaped crystals which resemble selenite in morphology, although the original mineral has been pseudomorphically replaced by dolomite (Section 4.4c).

Packing is variable from grain- to mud-support. In general there is a high proportion of interstitial mud, but mud-free areas do occur. The main bioclastic element is foraminifera which comprise 70-80% of the lithology in places (Plate 36e-f). Planktic Globigerina and benthic rotalinids are numerically the most important, but many less prolific forms are also found.

Subsidiary biotic components include molluscs, corals and algae. Algae are present as wisps and coatings on grains and as rhodoliths and encrusted nodules. Codiacean algal debris also occurs and patchy blue-grey mottling reminiscent of "birds-eye" texture (Shinn 1968b) is attributed to algae. Molluscs are frequently leached out and include finely ribbed and coarse robust bivalves, and rare small gastropods. Both tabular and branching morphologies of hydrozoan coral and branching and cerioid scleractinian corals occur rarely, but are generally highly fragmented. Bioturbation is common, and where present tends to disrupt the laminae and homogenise the sediment (Plate 30e). Rarely micrite filled vertical burrows can be seen. Inorganic framework constituents include glauconite pellets, terriginous detrital quartz grains and authigenic clay. High concentrations of fine pyrite are present locally.

The degree of abrasion of bioclasts is variable. Some delicate benthic foraminifera and thin shelled bivalves exhibit almost no abrasion, but elsewhere units contain predominantly comminuted biodetritus and disarticulated fragmented molluscs. Intermittently hydrodynamic reworking of wackestones has produced a nodular layering of creamy-buff muddy intraclasts separated by wavy lamination (Plate 34e,f). Nodules are frequently interconnected, and are ellipsoidal to irregular and elongate in shape. The subhorizontal flattening or intraclasts suggests that the nodules were unconsolidated at the time of deposition.

3.2.3 Algal Boundstone

(a) Distribution and thickness

Within the cores studied, this facies displays a close spatial association with the coral intraclastic floatstone-rudstone facies, and is encountered in the Duma-3 -5, and -11, Nurbani-4 and ZU-3 wells. None of Prior's (unpub. ARCO report) descriptions of the facies from the ZU-1 well correspond closely with this facies. The maximum thickness recorded in the wells logged is 12' (3.6 m.) in ZU-3.

(b) Texture

The facies is composed of thinly interlayered units of lime mudstone and poorly sorted bioclastic-calcareous algal wackestone. Stratification is enhanced by the presence of regular to buckled lamination, and diffuse swirling fenestrae mottled blue-grey to grey-buff (Plate 31) resembling "birds eyes" (Shinn 1968b) are common. The morphology of the calcareous algae varies from an irregular compact mass to a mammillated crust. Where present, the subhorizontal algal layers are anastomosing and of variable thickness. They are composed of mottled muds and foliose corals separated by lenses of sparsely skeletal lime mud, silt, or rarely winnowed grainstone.

The grain size is mainly fine silty micrite although floating algal rhodoliths and irregular abraded coral fragments upto 20 mm. long are present (Plate 31e).. Unabraded foliose corals upto 45 mm. long occur in lenses of coral rudstone-framestone (Plate 31c). The main constituents of the facies are algae, corals and cream to dark grey, pyritiferous, bioclastic lime mud intraclasts with locally, a diverse assemblage of planktic and benthic foraminifera including Miogypsina, Lepidocyclina, Globigerina, miliolinids and other rotalinids. Echinoid fragments, bryozoa and molluscs are rare. Calcareous red algae encrust corals and form semi-rounded and ellipsoidal rhodoliths (Plate 35c). Algal nodules, which are often amorphous retaining little cellular detail, rarely comprise upto 30% of the rock. Coral interstices are encrusted and bored by algae and filled with micrite.

3.2.4 Shelly Foraminiferal Rudstone-Floatstone

(a) Distribution and thickness

The facies occurs in all wells studied in the Duma and ZU fields except for Duma-9 and -11, but is not present in the Nurbani Field. Thickness varies between 1' (30 cm.) in ZU-4 and 6' (2 m.) in ZU-3. It generally occurs within the coral intraclastic floatstone as a very distinct interval and the upper and lower boundaries, where visible, are sharp.

(b) Texture

The matrix is micritic, buff in colour and commonly speckled with blue-black silt and fine-sand grains. The texture varies from wackestone to packstone, grading rarely to lime mudstone, and is sometimes algally mottled. Sedimentary structures are absent.

Large unabraded Lepidocyclina and articulated bivalves upto 35 mm. long are the main biogenic component. The fossils exhibit no consistent orientation and are packed loosely in a haphazard 'cardhouse structure' suggesting rapid disorganised deposition (Plate 34a). Packing varies from matrix to framework support. The sediment is bimodal the upper mode comprising the large shells and benthic foraminifera, and the smaller mode comprising foraminiferal packstone or wackestone.

Rarely, the large foraminifera are encrusted with calcareous algae. Towards the base of the unit the texture is conglomeratic and the foraminifera and shells are associated with rhodoliths and dark-coloured intraclasts. In the ZU-3 well there is a thin layer of fine rippled sand at the base of the shelly foraminiferal rudstone interval.

3.2.5 Sandy Impure Grainstone

(a) Distribution and thickness

This facies was observed in the Duma-11 well only. According to seismic data this level corresponds to the Duma Carbonate Buildup (pers. comm. M. Loos 1983) which is described as a 'late-stage clastic bar' overlying the Duma Limestones (Internal IIAPCO report unpub.).

On the evidence of seismic cross-sections, the facies is assumed to be present at the site of Duma-9 above the interval that was cored. Highly impure lime mudstone-claystone is encountered in the Duma-5 and Duma-3 wells at the level of the Duma Carbonate Buildup (Fig. 33), this lithology being the lateral equivalent of the sandy impure grainstone facies. The latter is restricted to the south and south-western flanks of the Duma High and the former to the east and north.

The sandy impure grainstone facies is 14' (4.6 m.) thick in the Duma-11 well - the only place that it was cored.

(b) Texture

The facies comprises a coarse-grained well-sorted framework-supported limestone. The colour is speckled black, buff and dark brown with clasts of greenish and pinkish argillaceous material (Plate 32). The grain size is variable from medium sand to granule-grade, with rare structureless slightly fissile layers and pods of mud (Plate 32d). Fine bedding laminae defined by alternating layers of detrital clastic and carbonate grains (Plate 32a,e) are 2 to 3 mm. thick and generally flat-bedded or inclined in shallow 15^{o} cross-beds. Stratification is accentuated by the rare presence of foliose corals. Cross-bed sets are upto 15 cm. thick and flat-based and mud rip-up clasts are common, generally very flattened and upto 20 mm. long. Particle orientation is pronounced.

Allochemical components include abundant glauconite grains with abraded forminifera, shell fragments, echinoid spines pellets, intraclasts and indeterminate skeletal grains (Plate 35d-e). Argillaceous clasts are well rounded and occur in layer concentrations. Soft crumbly argillaceous pinkish-buff material occurs as discrete grains, encrustations and void fillings, having been compacted into interstices. The green and black glauconitic grains are indurated and upto 40 mm. in diameter.

The interstitial matrix is generally tight but in patches has a powdery texture. Towards the base of the sandy impure grainstone interval, the lithology differentiates into friable layers rich in glauconite and tight dense cemented finer grained units. At a depth of 2316' (71.8 m.) in the Duma-11 well the lithology grades into packstone with floating coral fragments but lacking significant amounts of terriginous grains and glauconite.

3.2.6 Sparsely Fossiliferous Wackestone-Lime Mudstone

(a) Distribution and thickness

The facies is present in all three fields. In the ZU field it is present in the north and north-west, but only to a very minor extent in the thick carbonate section south of the ZU-high in the ZU-3 well. In the Duma field, the facies is present to the east of the high, and in the Nurbani buildup the facies is evidenct in the western part of the field, and attains a thickness of 160' (49 m.) in the western part of the Nurbani-3 and -4 wells, although since the core was not sleeved this material was not recovered.

(b) Texture

The rock is buff to pale grey in colour with intermittent subhorizontal dark brown laminae (Plate 33). The texture is mainly earthy, soft to stiff and fine grained and the argillaceous content is variable tending to decrease downwards. Texturally it is quite homogeneous in character, varying from lithographic to slightly fissile. The fine laminae are defined by colour and grain size, being paler and slightly siltier than the matrix, and are from 0.5 to 2 mm. thick. Wispy discontinuous partings (Plate 33a) and subhorizontal very elongate lenses from 0.5 to 2 mm. in thickness and upto 30 mm. long (Plate 33c), are present, accentuating the layering in places. Downwards the texture becomes increasingly silty and fossiliferous, grading to a buff wavy bedded calcarenitic wackestone (Plate 33b) and ultimately into the algal boundstone or conglomeratic coral floatstone facies.

Bedding and sedimentary structures are rare, although occasionally, an interlayering of pale brown mudstone and wackestone is apparent. In this area also, there are rare cross beds and graded beds generally occurring in sets 15 cm. thick. Graded beds contain units of semi-indurated shingle interpreted as periodic incursions of coarse storm-derived detritus. Scattered fine black grains are common and may be of terriginous origin. The lime muds contain a sparse indigenous fauna of low diversity and numerical abundance, which increases downwards. The lithology is mainly unbioturbated although locally pale to medium brown diffuse mottling is attributed to biogenic reworking of the muddy sediments (Plate 33a). Most of the particles interpreted as being of skeletal origin are blebs of micritised cream-coloured carbonate which cannot be assigned to a particular faunal group.

Leached, mud-filled, bored hydrozoan and scleractinian coral fragments, fine, unabraded, delicate shells and benthic foraminifera upto 60 mm (Plate 36a) long are rarely present. Occasionally wisps of calcareous red algae and small patches of stromatolitic fabric are preserved. Rare lenses of skeletal packstone contain slightly fragmented planktic and benthic foraminifera. In the Nurbani area only, there are a number of hard vuggy bands upto 12 cm. thick with sharp upper and lower boundaries, composed of highly indurated coral or skeletal packstone.

3.2.7 Coal

(a) Distribution and thickness

The facies occurs in a 30 cm. thick band in the Duma-11 and Duma-9 wells only. Coal probably developed over part of the ZU area although is not encountered in the wells examined. Carbonaceous partings are evident at a depth of 2799' (933 m.) in the ZU-3 well and wood fragments admixed with carbonate and terriginous grains at 2626' in the ZU-1 well (Plate 36c). The Talang Akar High underlying the Nurbani buildup was completely submerged throughout the period of carbonate deposition, and so no coal formed there. Coal has been described from the lower part of the Batu Raja Formation in the Krisna and Selatan fields (Wight, pers. comm. 1984).

(b) Texture

The coal grades upwards from a highly leached obliquely laminated, slightly argillaceous, foraminiferal-mollusc packstone-wackestone (Plate 36d). The packstone laminae are slightly glauconitic, 2-4 mm. thick and contain occasional horizontally flattened coal lenses.

The coal itself is intensely burrowed, dull brown-black to vitreous in lustre, and contains scattered cream-coloured foliose coral fragments. The burrows are subhorizontal possibly indicative of a shallow layer of nutrients. The stained and abraded coral fragments are 5-10 mm in size and are clearly transported by wave action.

3.2.8 Interpretation

The size, shape and disposition of all buildups within the Batu Raja Formation of this area, are related to the underlying tectonic framework and local structural control. Study of the cores suggests that coral framestone represents a very minor component of the buildups, limestone textures and compositions consistently indicating a peri-reefal provenance even in wells such as Nurbani-6 which penetrate the growing core of a buildup.

Evidence from wells drilled through Pliocene-Holocene reef rock in Funafuti (Rodgers 1980), Eniwetok and Bikini (Braithwaite 1973) however, suggests that destructive processes active in reef rock rapidly render framework unrecognisable. The second Funafuti reef boring of 1898, drilled on the seaward side of the atoll, reportedly struck cavernous rock. In the top 150' (45 m.) only 8% of the material was consolidated, four-fifths of the core being composed of bioclastic-foraminiferal debris. Corals played a relatively minor role and were as often in situ in the top as in the lower part of the well. Rodgers (1980) stated that cavities were filled mainly with foraminiferal and algal detritus, the former sometimes constituting the bulk of the rock. Thus, in view of the poor preservation potential of the reef framework, the sparsity of identifiable framestone in the Miocene Batu Raja limestones is insufficient evidence to infer that a coral framework was not formerly present.

Upon initial examination, the facies appear to have a random vertical distribution in several of the wells, e.g. Duma-3, -9, -11, Nurbani-4 and ZU-4. A suite of lithologies, however, is to be expected in each environmental zone resulting from variations in local sediment productivity, exposure to currents, growth framework and other factors. Comparison with modern reefal examples allows probable environments of deposition and palaeodepths to be postulated for each ancient facies. Study of cored facies sequences then suggests that two or more cycles of deposition occurred during the period of Batu Raja sedimentation, the cycles being controlled by periodic transgressions and regressions. These relatively small-scale movements in water level are superimposed on the overall transgressive trend which dominated the Batu Raja carbonate sedimentation pattern. Several repetitions of sequences occur in the wells studied (Appendix 4) each of which is capped by intraformational discordances. The cored material is in pieces most of which are 10-50 cm. long and in many cases the discordance is inferred between two pieces which exhibit contrasting characteristics in interpreted environment of deposition (Section 3.6.2). Discordances are visible in several of the cores, particularly within the sparsely fossiliferous wackestone-lime mudstone facies and capping the coal units. In the Duma-11 (2358'), -9 (2298'), -5 (2404') and ZU-4 (2630') wells there are several such leached semi-indurated surfaces of low relief, marking a hiatus or change or character of sediment deposition.

The discordances identified between repeated shallowing-up sequences may be a result of local basement subsidence or rapid transgression. The former cause is considered to be the most likely for two reasons; firstly because the discordances are very localised and not correlateable between wells and secondly because the contact between the shallow water lagoonal muds and deep water overlying coral rudstones in the Duma-3 and -5 wells for example, is sharp.

In the ZU field, the isopach map for the top of the Formation (examined courtesy of S. Prior, ARCO) shows that the carbonates were deposited as a series of discrete buildups elevated above a platform area. The factors controlling the precise loci of carbonate proliferation are small-scale and not detectable on seismic or isopach maps. Examples of palaeo-landforms which could provide a favourable substrate for colonisation by carbonate-secreting organisms are documented in Section 2.7. The Pliocene Kais reef limestones of Irian Jaya (N. Hendry pers. comm. 1984) and the Miocene Terumbo buildups of the South China Sea exhibit a similar growth configuration to those of the ZU Field.

The contrast in limestone textures apparent to the north-west and south of the basement ZU High (Section 3.1.3c) might be due to the effect of this topography on the hydrological regime. From the distribution of shaly and massive carbonates, it is inferred that wave fetch was from the south and east. Across the western side of the topographic ridge, wave energy and water agitation were dissipated, producing a lee area which was relatively sheltered and hence not conducive to vigorous coral growth in contrast to the probable deeper water to the south in which the massive carbonates of ZU-3, -4 and -1 were deposited. It is also evident from the inferred palaeodrainage map, that most of the rivers drained northwards from the ZU High during and prior to the period of deposition of the Talang Akar sediments. Prior to the flooding of this High, which occurred in the latter part of the period of carbonate deposition, reef growth may have been inhibited in the north and north-west by contamination from fluvially-derived terriginous sediment, similar to the situation apparent in the southern part of the Pulau Seribu (Section 2.7). A further explanation for the thickening of the Batu Raja in the south and south-west is a tilting of the entire area to the south, although there is no evidence to substantiate this.

As in the ZU Field, high energy and low energy flanks are also inferred for the NNW-SSE elongated Nurbani buildup. The seismically-based isopach map for the top of the limestones (Fig. 34) shows an asymmetric structure with a relatively steep (windward?) ENE-facing flank sloping at approximately 15^{o} and characterised by a relatively high proportion of coral debris-rich limestones (Appendix 4), and a relatively gentle (leeward?) WSW-facing flank sloping at approximately 5^{o}, dominated by fine-grained bioclastic limestones (Appendix 4). Growth occurred towards the east and fine sediments were transported westwards into a low energy environment. The Nurbani-6 well lies on the northern flank, the Nurbani-3 and -4 wells on the platform-like top of the buildup, and the Nurbani-10 well on the western slope. The susceptibility of this buildup to drowning suggests that framework production was rapidly outpaced by the rise in sealevel. Since subaerially exposed basement highs do not occur in this field, facies belts were unable to migrate to shallower levels during periods of transgression, and thus carbonate deposition was rapidly terminated.

The character of carbonate sedimentation in the Duma area was influenced by the basement relief to a greater extent than in the Nurbani and ZU reservoirs since the Duma High remained above sealevel throughout the period of deposition of the Batu Raja Formation. In this area, the limestones clearly fringed the High and at no time extended over its crest. Differences in the relative proportions of the sparsely bioclastic lime mudstone-wackestone and the coarse biodetrital lithologies around the High suggests that the south and west flanks (Duma-9 and -11) were relatively exposed compared with the sheltered eastern flank. The Duma-5 and -3 wells in the sheltered localities contain considerably thicker carbonate sequences than those in exposed localities, but the proportion of sequence represented by the coral-intraclastic rudstone facies is relatively less.

3.3 RAJAMANDALA FORMATION

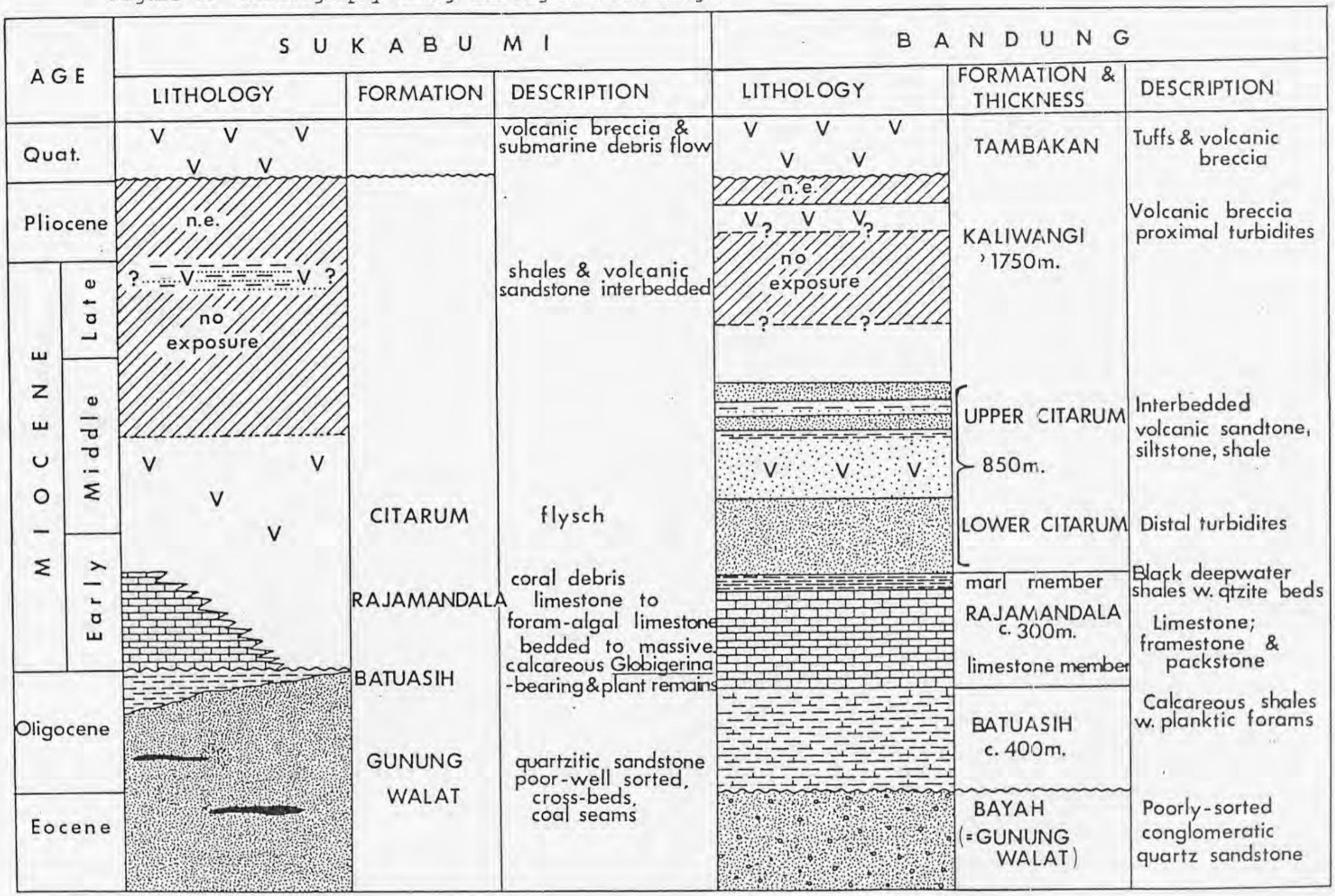
3.3.1 Structure and Stratigraphy

The Rajamandala Formation (= Tagog Apu Formation, van Bemmelen 1949) and immediately overlying units are exposed in a number of working quarries north-west of Bandung, and around Sukabumi, West Java. The Rajamandala reefs developed during the Oligo-Miocene on a shallow water platform, south of the deep sea sediments of the Bogor Trough (Koesoemadinata & Siregar 1984). These reefs are therefore slightly older than those of the Batu Raja Formation. The stratigraphical position of the Rajamandala Formation in its regional framework is illustrated in Fig. 35. Due to the palaeogeographical evolution of West Java (Fig. 36), the Bandung-Sukabumi area was flooded slightly before the present south-west Java Sea area.

The Rajamandala Formation is exposed mainly along the discontinuous WSW-ENE trending Rajamandala Ridge, stretching from just WNW of Bandung, to Sukabumi (Fig. 37), a distance of approximately 80 km. The ridge rises to 250 m. above the Bogor-Cirebon plain to the north and the carbonates are deposited along the northern edge of a southerly dipping offself platform (Koesoemadinata & Siregar 1984). Its physiographic elevation is also partly due to thrusting (Martodjojo 1983). The formation is between 120-150 m. thick at the eastern end of the ridge, but complex structure and numerous thrust faults result in thicknesses of upto 600 m. in the Bandung Area (Harting 1929; van Bemmelen 1949). Beds dip between 45^{o} and 90^{o} to the south and some are overturned.

At the north-eastern end of the ridge, dense massive beds of limestone

Figure 35 Stratigraphy along the Rajamandala Ridge.



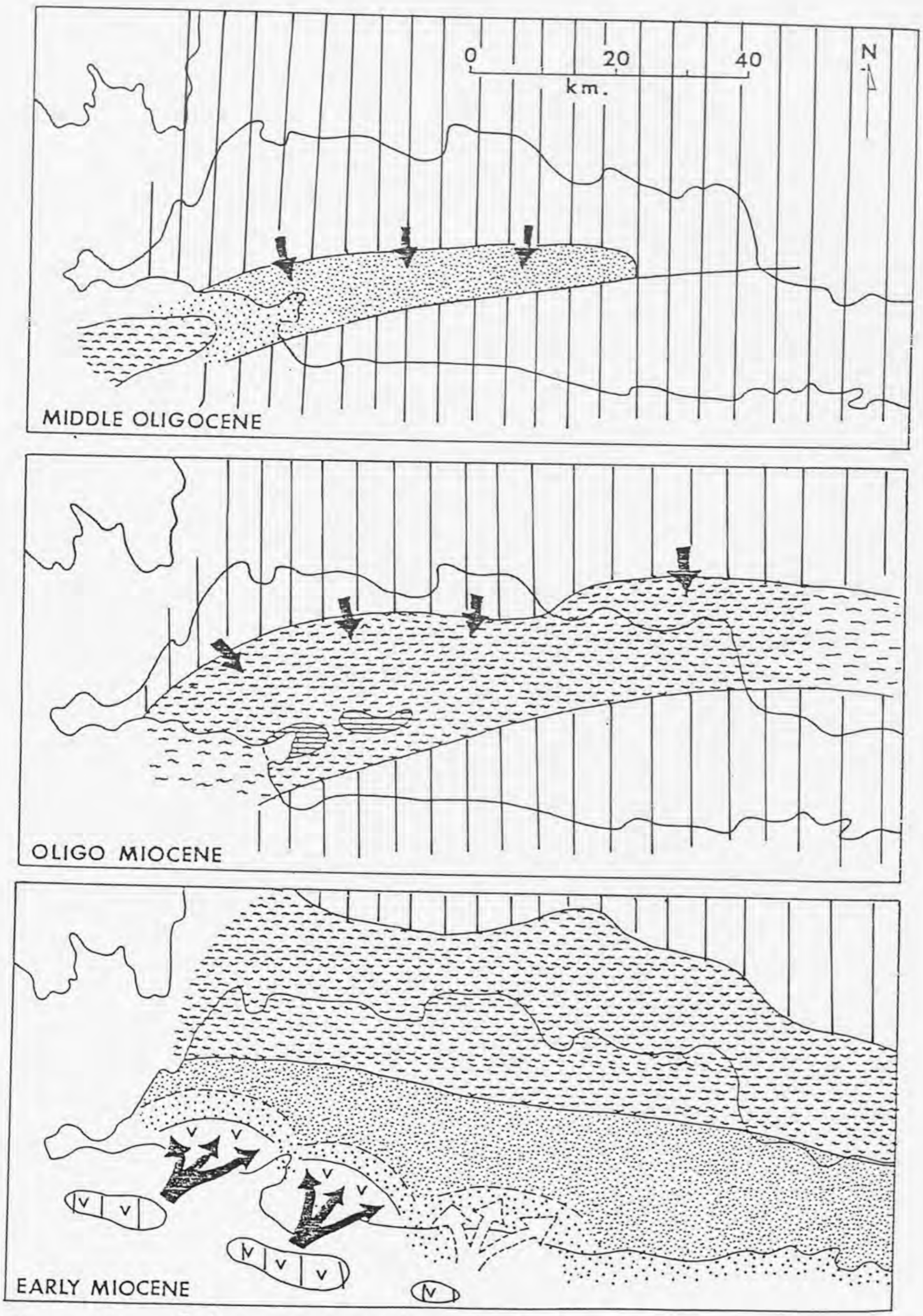


Figure 36 Palaeogeography of West Java
(a. Soejono Martodjojo 1983)

shallow seas
land area
active volcanos
sediment movement
shallow water deltaic sediments