ABSTRACT

The East Java Sea displays excellent examples of Miocene to Present-Day structural inversion of a Palaeogene extensional/transtensional basin system. The structural geometry of these inversions has been analysed by a series of regional cross-sections which demonstrate significant lateral variation in structural style. This variation is interpreted to be a function of the fault shape and linkage which evolved during the extensional phase of basin development. Prediction of fault geometry has been aided by analogue-modelling of inverted extensional basins.

Driving mechanisms of structural inversion have been assessed by modelling the motion of the Eurasian, Indian Ocean, Australian and Pacific plates during the Neogene. The evolution of inversion within the East Java Sea is interpreted to be a function of the propagating collision of the Australian Plate with the Sunda Arc, and the resultant variation in relative convergence rate and direction of the subducting Indian Ocean Plate and the S.E. Eurasian Plate.

Stratigraphic evolution is strongly influenced by relative sea level fluctuations, principally eustatic, within overall control of tectonic processes, particularly inversion. The sediment fill is mainly fine-grained with alternating carbonate-dominated and clastic-dominated cycles.

The use of wireline logs, seismic data and biostratigraphic data allows a detailed sequence stratigraphy to be developed, with both regionally and locally recognisable highstand, lowstand and transgressive systems. A well-imaged progradational carbonate platform margin exhibits late-stage growth and subsequent inundation which are used to calibrate locally derived relative sea-level curves.

INTRODUCTION

The East Java Sea Basin is part of the system of back-arc basins developed around the margins of the Sunda Shield, from North Sumatra to Central Sulawesi. Onshore East Java is well explored and has been producing oil since the late 19th century. Exploration of the East Java Sea began in the early 1970's and has proven significant gas reserves (including Pagerungan and BD), and a number of currently sub-economic oil and gas finds. BP's involvement in the East Java Sea Basin commenced in 1982 with Hudbay in the Madura Strait PSC. Currently BP holds the three Lombok PSCs (Sakala Timur, Satanger and Sabilit), and is also a partner in the Kangean PSC, operated by ARBNI.

The nine discoveries in the main basin area occur in eight different play types, largely a function of the stratigraphic variability. Although some areas of the basin are complex structurally, it appears that many well failures are due to difficulty in predicting the lateral distribution of reservoir and source facies. With the benefit of a large seismic database BP has undertaken regional basin analysis in order to improve understanding of the basin evolution and in particular the relationship between tectonics and sedimentation.

The principal objective has been to identify the full extent of individual depositional systems ('systems tracts'), their seismic boundaries, and the structural and eustatic controls on their deposition. The resulting sequence framework has been used both to understand lithofacies distribution in known fairways and also predict potential new fairways.

Basin Distribution and Tectonic Setting

The regional tectonic and structural framework has been established by Hamilton (1979), and subsequent research has been largely built on this original work. The recently published structural interpretation of fault reactivation on the eastern Sunda shelf (Letouzey et al. 1990) provides an excellent introduction to the regional
structural problems. Our intention here is to develop these arguments by analysis of the detailed stratigraphic and structural evolution based on geometrical relationships and sequence distribution in both map-view and cross-section.

The sub-basins of the East Java Sea are part of an extensive and complex basin system which has developed around the margins of the SE Eurasian Plate (Figure 2). The orientation of major fault zones which define these sub-basins varies around this margin. Three distinct trends are recognised. In the area of the Makassar Basin the main fault systems are orientated approximately NE-SW, parallel to the coastlines of East Kalimantan and West Sulawesi which form the flanks of the basin. Faults of this orientation continue SW into the East Java Sea where they define major sub-basins such as the Masalima Trough, Central Deep and Muriah Trough. Important NW - SE trending faults are present within the Makassar Basin, notably north of the Paternoster Platform and in the Salayar Basin area offshore SW Sulawesi. The third major fault trend is best developed within the southern part of the East Java Sea, where the major sub-basins are defined by faults which trend approximately E-W.

The current tectonic framework of this area results from the motion of the Eurasian, Indian Ocean-Australian, and Philippine Sea Plates (Figure 3). Motion of the Indian Ocean plate is approximately towards the north and the Philippine Sea Plate approximately towards the WNW (Daly et al. 1991), both plates converging on the relatively stable Eurasian Plate. Convergence along the southern margin of the Eurasian Plate is taking place by subduction of Indian Oceanic crust and by westerly propagating collision of the Australian continental crust with the island arcs to the north of the Sunda Trench. Along the eastern flank of the SE Eurasian plate convergence is being accommodated by subduction of the Philippine Sea Plate. The largely oblique direction of motion of both the Indian Ocean and Philippine Sea Plates to their respective trenches may be the fundamental control on strike-slip fault development within the back arc and magmatic arc areas, originally proposed by Fitch (1972) for the Indian Ocean example. The resultant strike-slip features are the Sumatra Fault (Semanko Fault) and the Philippine Fault.

**Sequence Stratigraphic Analysis**

Major fault systems divide the East Java Sea Basin into a number or discrete structural provinces. Within many of these the sediment fill is layer cake due to aggradational deposition. Diagnostic seismic geometries and stratal terminations, which normally occur in shelf break and slope areas, thus are rarely observed, and many of the steep faults/flexures form important facies boundaries. Other facies boundaries occur at poorly imaged carbonate margins. In both these situations little or no sequence information is deriveable from seismic data. Neither can seismic interpretation of a single structural province provide all the clues to sequence development, since only one part of each depositional systems tract may be present. Often correlation between structural provinces is dependent on biostratigraphic data, and where dating is poor, inconsistencies between lithostratigraphy and chronostratigraphy can lead to some rock units being assigned to incorrect sequences.

This has been resolved by an understanding of the tectonic and eustatic controls on basin development. The proposed sequence stratigraphy is the result of analysis of a large seismic and well dataset. Seismic sequence analysis was carried out in the few key areas showing diagnostic reflector patterns, in particular platform areas in the north of the Lombok and Kangean PSCs (Figure 2). Structural analysis facilitated identification of those sequence boundaries caused by local tectonic effects, rather than eustasy or regional uplift. Regional identifiable seismic boundaries discussed in this paper include both flood surfaces (Galloway 1989) and erosional boundaries. Sequence boundaries discussed below are highlighted for their practical usage in defining basin fill, and their value in erecting a eustatic sea level curve. Sequence boundaries were tied to wells, and wireline logs were used to more accurately define the sediment package represented by the seismic sequence. The lithostratigraphy and the palaeoenvironmental analysis of each sequence were subsequently incorporated into regional palaeofacies maps. The principal objective is to assist lithofacies prediction, particularly of potential reservoir and source facies, both in known fairways and frontier areas.

**BASIN DEVELOPMENT**

Three tectono-stratigraphic megasequences are identified on seismic data and other criteria (Figure 4). These have developed in response to plate margin processes since late Cretaceous (Figure 5). Beneath a peneplane surface a highly structured and deeply eroded folded belt of probable Cretaceous age is locally recognised (Figure 6). The overlying Tertiary section can be subdivided into two further megasequences: the Palaeogene megasequence is characterised by sediment expansion into a complex of rifts trending roughly W-E along the basin axis, flanked by platformal areas with thinner deposition. The Neogene megasequence is characterised by onset and continuation of inversion,
which fundamentally changed the basin architecture. The depocentres of the Neogene inversion mega-sequence were shifted away from the uplift zones, principally into a major thick to the south.

Away from areas of rifting/inversion, Tertiary subsidence has been essentially constant and passive, with no significant structural/stratigraphic breaks. The two-fold subdivision into rift and inversion megasequences is not clearly recognised, and these areas are frequently the sites of carbonate platform growth throughout the Tertiary.

**PRE-TERTIARY**

**Plate Tectonic Setting**

Regionally, onshore constraints from SE Kalimantan (Sikumbang, 1986), Sulawesi (Hasan, 1991) and Java (Ketner et al, 1976) support the hypothesis of Hamilton (1979) that the East Java Sea is underlain by a basement of quite different composition and origin to the Sunda Shield to the northwest. Most of this basement material has accretionary affinities. Metamorphic radiometric dates range from latest Jurassic through to late Cretaceous, with an apparent modal peak in the mid Cretaceous. All of the currently published outcrop and well constraints can be reconciled by invoking a late Cretaceous collisional event between an East Java Sea microplate and the southeastern part of the Eurasian Plate. Prior to this collision the motion of the East Java Sea was accommodated by subduction at a trench which is interpreted to be aligned with the "approximate southeast limit of Cretaceous continental crust" (Hamilton, 1979) (Figure 5). This postulated collision will have resulted in the switching of tectonostratigraphic zones, so that the forearc and magmatic arc locations switched several hundred kilometres to the southeast between latest Cretaceous and earliest Cenozoic (Figure 24).

**Stratigraphy and Structural Analysis**

The pre-Tertiary tectono-stratigraphic units recognised in the East Java Sea and SW Sulawesi are summarised in Figure 7 and their areal distribution in Kangean/Lombok in Figure 8. Two distinct units are recognised, a widespread heterogeneous accretionary complex, locally overlain by well bedded Upper Cretaceous sediments.

a). Accretionary Basement

Many wells in the SE Sunda Shield area reach total depth in a variety of highly indurated and tectonised meta-rocks, including quartzite, chert, conglomerate, volcanics, slate, high grade metamorphics and ophiolitic suites. These are traditionally interpreted as accretionary material, particularly in the light of regional data, as detailed below. In the Kangean/Lombok area (Figure 7) at least four wells penetrate pre-Tertiary rocks which can be assigned to this tectono-stratigraphic unit. Rock types include metavolcanics, quartzite, chert and serpentinised amphibolite.

b). Upper Cretaceous Sediments (Megasequence I)

New seismic data in the East Java Sea Basin and outcrop data in SW Sulawesi (Hasan, 1991; Garrard, 1992) shows fairly widespread and thickly developed Upper Cretaceous sediments, which appear to lie structurally and stratigraphically above the accretionary complex (Figure 8).

In the Kangean/Lombok area discrete synformal erosional inliers are mapped (Figure 7), which are well imaged seismically (Figure 6). The sediments subcrop the basal Tertiary reflector at a high angle, and internally are well bedded. Numerous faults cut the section, but it is not highly deformed. Numerous wells (Figure 7), penetrate highly indurated and thermally overmature (%Ro 1.3 to 1.8) sediments. The overall section is mud-dominated, with lesser siltstone and some tightly cemented, lithic to sub-lithic sandstone interbeds. Structural complexity in the area of the well penetrations means that stratigraphic relationships are unclear. Broad correlation suggests lower sequences are grey to grey-black in colour, with rare late Cretaceous marine microfossils. Several wells penetrate red beds which appear to be higher stratigraphically. Seismic interpretation has not demonstrated stratigraphic breaks in the unit; some well data suggests however that the "pre-Ngimbang Fm" (Phillips, 1991) (Figure 8) may represent a separate sequence of possible Tertiary age.

The base of the package is generally high amplitude, and clearly imaged on true amplitude seismic sections. There is local onlap onto this event and subcrop beneath it, suggesting a major unconformity. The section beneath is locally a discontinuous, contorted seismic facies with poor signal penetration, or else seismically transparent. At least four wells penetrate areas outside the subcrop limits of the bedded Cretaceous; the combination of the lithotypes (see above), and the seismic observations suggests that these wells penetrate the subcrop of the accretionary complex beneath the base of the Tertiary. This is effectively acoustic basement, whereas the bedded Cretaceous represents economic basement.

Age equivalents to the bedded late Cretaceous include...
Following the accretion of the East Java Sea microplate, the current distribution of the erosional possibility is that the latter post-dated the accretion lineaments will have controlled subsequent basin formation and deformation (Letouzey et al., 1990). Plate Tectonic Setting

YALAEOGENE (MEGASEQUENCE)

The compressional geometries are likely to be a result of late Cretaceous collision, although the temporal relationship between accretion and late Cretaceous basin formation and deformation is unclear. Another possibility is that the latter post-dated the accretion phase. The current distribution of the erosional remnants of late Cretaceous basins is adjacent to the reconstructed plate margin in the late Cretaceous (Figure 5). The structural style and limited facies data is consistent with basin formation and deformation in a forearc setting at an oblique plate margin.

It is likely that the fundamental structural grain of the East Java Sea area was created during these phases. In a strongly heterogeneous basement pre-existing lineaments will have controlled subsequent basin formation and deformation (Letouzey et al., 1990).

PALAEogene (MEGASEQUENCE II)

Plate Tectonic Setting

Following the accretion of the East Java Sea microplate during the late Cretaceous, active subduction proceeded around the margin of the newly modified SE Eurasian Plate (Figure 5). Palaeogene volcanics are known from West Sulawesi and also from East Java Sea well sections. During the Palaeocene and early Eocene the northward motion of the Indian Ocean Plate was being accommodated by subduction of Indian Ocean crust along the Sunda Trench. To the east, around the Sulawesi portion of the margin, it is probable that active subduction of the Pacific Plate was in progress as it moved in a W to NW direction relative to Eurasia. Numerous models have been proposed for the plate configuration at this time, it is possible that the Indian Ocean Plate was moving north past West Sulawesi to the east of a major transcurrent fault. An alternative, and the preferred interpretation here, is that Pacific Ocean crust was being subducted beneath West Sulawesi during the Palaeogene to explain the distribution of Palaeogene magmatism.

The onset of rifting within the East Java Sea is broadly coincident with the collision of the Indian continent with Eurasia and the reorganisation of the Pacific Plate during the Middle Eocene. The resultant reduction in convergence rate around the SE Eurasian Plate, possibly resulting in subduction roll-back, is a plausible mechanism for back-arc extension around the margins of the SE Eurasian Plate. The variable rates of subduction around the arc during and after the Indian collision and Pacific Plate reorganisation are likely to be the fundamental control on stress vector variation, and hence fault movement sense, throughout the Palaeogene.

Structural Response

A detailed understanding of the East Java Sea rift history is fundamental to the analysis of stratigraphic fill discussed later. Localised extension was underway by early Eocene (P9/P10), and rifting was very widespread by late Eocene, based on interpretation of the geometry and timing of motion on major faults, which show a marked stratigraphic thickness contrast from hangingwall to footwall for time equivalent sequences. The geometry of these major faults has been assessed from both maps and cross-sections as this provides the maximum constraint on 3D rift geometry. Typical Palaeogene structural and stratigraphic geometries are displayed on Figure 9, and the distribution of Palaeogene isopach thickness is displayed on Figure 10.

a). Map view

The map pattern of major Palaeogene fault zones shows a broadly E-W trend. The most laterally continuous of these is the Sepanjang Fault Zone which
defines the southern limit of the Palaeogene depocentre of the Kangean and Lombok Central Troughs. To the north of the Sepanjang Fault, a system of NE-SW to WNW-ENE faults show major Palaeogene thickness variations from hangingwall to footwall.

The most laterally persistent of these more northerly faults is the Sakala Fault (Figure 11), a steep fault which dips to the south within the Kangean Block. The western lateral tip of the Sakala Fault is located near to the southeast limit of Kangean Island, but is poorly imaged. To the west of this there is evidence for a switch in polarity of the Palaeogene fault system as the Palaeogene thickness of the Kangean Island area exceeds substantially that to the north of the Sakala Fault. This may be explained by a northerly downthrowing fault controlling the Kangean Island depocentre in its hangingwall. The eastern extension of the Sakala Fault to the east of the Kangean PSC becomes more complex involving several ENE-WSW trending faults, both north and south dipping. It is unclear from current constraints whether displacement on the Sakala Fault dies out at a lateral tip or is continuous laterally with one of the faults within this eastern system. The overall sense of displacement is down to the north. Unraveling this geometry is critical to understanding the Palaeogene movement sense on the Sakala Fault. From map geometries within the Kangean PSC the Sakala Fault appears to be most simply interpreted as a Palaeogene normal fault with consistent sense of downthrow to the south. If the Sakala Fault is continuous with a major north-dipping fault to the east then the sense of throw changes along-strike, in which case the movement history is likely to involve an important strike-slip component.

The Sepanjang Fault can be traced from the south of Sepanjang Island in an approximately E-W direction for a distance in excess of 150 km. Palaeogene thickness variations across this structure indicate a consistent sense of downthrow to the north with the Palaeogene depocentre located in the hangingwall to the north of the fault. Using Palaeogene geometrical constraints the fault can be most simply interpreted as a normal fault zone. This fault zone is continuous to the south of the zone of polarity switching along the Sakala Fault, and as a result the regional Palaeogene basin geometry changes along-strike from a graben in the area of the Kangean Central Trough to a half-graben in the area of the Lombok Basin (Figure 12).

Within the Southern Basins, south of the Sepanjang Fault, the Palaeogene fault geometry is less well constrained as a result of the very thick Neogene section over much of this area. East of 116 degrees the geometry is better imaged, and the major extensional faults show a WSW-ENE trend with the map geometry again most simply explained in terms of dominantly normal fault evolution. A major horst is interpreted south of the Sepanjang Fault in the area south of the L 49-1 well, a Palaeogene structural high which can be traced at least 75 km along strike, bounded by counter dipping normal faults (Figure 9).

In summary, the Palaeogene fault geometry in map view is most simply explained in terms of a dominantly normal fault evolution with important polarity switches in the northern part of the basin. The key question concerns the fault linkage at these polarity switches, if they can be shown conclusively to link then a regional strike-slip component to the movement history (in addition to the obvious dip-slip component) may have to be invoked. This point is returned to later in the paper.

b). Cross-sections

Structural geometries are displayed on Figures 11 and 12. Palaeogene faulting was initiated by the middle Eocene in the Lombok Central Trough and Southern Basin, based on preserved thickness variations observed in the footwall and hangingwall of the Sepanjang Fault. The major variation in preserved thickness within the Kangean Central Trough is observed during the late Eocene and early Oligocene, this relationship being well displayed by the geometry in the hangingwall and footwall to the Sakala Fault. Geometrical relationships along strike within the Lombok Central Trough suggest a westward continuation of the rift phase which had been initiated there earlier in the Eocene. These observations do not necessarily demonstrate two-phase rifting, they merely suggest that the timing of onset of rifting varies along the length of the East Java Sea.

The regional half-graben geometry is apparent on Figure 12, with the Sepanjang Fault controlling this geometry. All Palaeogene structures interpreted on these cross sections are explicable in terms of a dominantly extensional evolution. In the area to the north of the main Sepanjang Fault (Figure 12), the geometry within the hangingwall is comparable to results of recent sand-box modelling of extensional basin geometries (McClay, 1990) involving the development of crestal collapse graben and intra-hangingwall horst blocks.

To the south of the Sepanjang Fault, the horst and half-graben geometry described earlier from map analysis is shown on Figure 9. On the regional-scale this geometry suggests an extensional Palaeogene evolution, however the detailed geometrical relationships within parts of this southern basin system demonstrate erosional
truncation of Upper Eocene sequences, suggesting the possibility of significant local uplift at this time. This may be a result of localised contractional uplift resulting from a transpressional component of motion. An alternative model of footwall uplift during a late Eocene rift event cannot be excluded. The relative importance of the dip-slip and strike-slip components of motion during the Palaeogene are discussed further later in this paper.

Palaeogene Stratigraphic Response

Indonesian backarc areas developed on crystalline terrains (eg Sumatra and NW Java) typically have a thick coarse clastic non-marine rift fill, and stratal patterns and isopachs demonstrate that high relief was preserved during rifting. In contrast only a small part of the East Java Sea rift fill is non-marine. Relatively thin continental sections are penetrated offshore East Java and in SW Sulawesi, but the bulk of the rift fill demonstrates marine influence, or is fully marine. Also much of the pre-existing land surface was peneplaned prior to the late Eocene. This erosional bevelling, and the early development of coaly facies in the rifts, suggests that rifting commenced close to marine base level, facilitating rapid inundation. The subsequent late Eocene transgression was very widespread, effectively shutting off coarse clastic input. Basement type clearly exerts a fundamental control on sediment fill, the bulk of which is fine-grained clastic and carbonate dominated. Subsidence outpaced sediment supply for much of the Tertiary; coarse clastics were restricted to proximal areas adjacent to the Bawean arch. Distal rifted areas became bathyal and were locally sediment starved. Widespread carbonate platform growth occurred on distal stable areas.

Palaeogene sequence stratigraphy and sequence terminology is summarised in Figure 13.

a). Ngimbang Clastics

The current lithostratigraphic term incorporates all Eocene aged clastics. The Ngimbang carbonate (see below) is currently the only regionally recognisable seismic marker within the Ngimbang Fm.

No definitive evidence exists for Palaeocene aged sediments. Onset of rifting occurred in early to mid Eocene (P9/ P10 or older). Sediments of this age are relatively restricted areally (Figure 10) although original limits of this rift system are difficult to establish due to later erosional truncation, tectonic overprinting, and poor seismic imaging (especially in western areas). The vertical facies development in the early to mid Eocene rift systems is transgressive with a gradation from non-marine (fluvial and ephemeral lacustrine), to coastal plain (frequently with coals), and marginal marine. This sequence is also observed in the Eocene rifts of SW Sulawesi. Locally, thicker fully marine sequences are penetrated (eg L 40-1), which may occupy positions closer to controlling faults. Internal sequence geometries are typically aggradational (Figure 9), implying low depositional gradients and diffuse lateral facies boundaries. Currently well log sequence stratigraphy is of more value than seismic stratigraphy in play fairway analysis.

Extension spread to a much wider area in late Eocene, with many new rifts developed in areas unaffected by the first phase (Figure 10). In these areas the oldest planktonic foraminiferal dates are P15, but the basal clastics and carbonate cannot be accurately dated, due to the lack of resolution in palynological and larger foraminifera schemes compared with planktonics and nannofossils. The influx of clastics in the late Eocene may be a result of hinterland uplift due to more widespread rifting at this time. The basal clastics in the late Eocene rifts show the same vertical facies development as the early/mid Eocene system, but are significantly thinner (Phillips, 1991). The internal sequence stratigraphy of this unit is close to seismic resolution. Lithofacies distribution is shown on Figure 14. Isopach thickening continued into the Oligocene. The entire section is probably not controlled by active rifting however; the upper section probably results from post-rift accommodation on faults and passive infill.

b). Ngimbang Carbonate (Sequence 30)

Continued transgression led to the widespread deposition of the Ngimbang carbonate, suggesting that little or no topography remained at this time, resulting in rapid transgression. Final flooding occurred in P15 resulting in the drowning of the Ngimbang carbonates except in internal structural highs, where reef growth continued, and around the basin margins where carbonate platforms developed. Much of the area developed bathyal conditions. Gamma ray maxima are developed in several wells in eastern areas (Figure 15) indicating conditions of partial anoxia may have been established by rapid widespread drowning.

c). Late Eocene Event (T34)

A significant tectonic event within the late Eocene (Figure 13) caused fairly widespread high angle faulting and subsequent erosional truncation. Areas affected include the L 46 structure, the Paternoster-1 area, and possibly the Pagerungan area. High angle faults affect much of the Southern Basin. Possible mechanisms have been discussed above. A prominent structurally induced
sequence boundary is observed, and the resultant topography is passively unfilled by deepwater sediments; on some elevated areas carbonates are observed to seed. Offstructure correlative conformities indicate no breaks in sedimentation, with continued net extension.

d). Mid Oligocene Unconformity (T36)

A prominent seismic reflector is identified over much of the Kangean/Lombok area which is pronounced on structural highs where it enhances and becomes indistinguishable from the late Eocene event (T34). Localised high relief channeling is recognised (Figure 16). The base of the overlying sequence is generally P20/21. In the east deepwater fine-grained sediments are developed above and below the unconformity. In central areas many wells record platform carbonates resting on bathyal mudstones (e.g. Bulumanuk 1, NSD-1D). In western areas thin mid Oligocene aged sands are penetrated (e.g. Ngimbang-1, Arosbaya-1; RRI 1986). The major shift in facies belts, the local channeling and the dating combine to suggest that this event is the mid Oligocene eustatic lowstand.

e). Late Oligocene (Sequence 38/40)

The late Oligocene in basinal areas consists of parallel bedded calcareous mudstone and limestone; the sequence is condensed suggesting sediment starvation. The uppermost carbonate is a regional marker of N4/5 age, the Prupuh Limestone. Detailed microfaunal analysis (T. Wonders pers. comm.) shows a clean, foraminifera rich limestone with a high percentage of pelagic fauna. The overlying N5/6 sequence is muddier and has a shallower water faunal assemblage. Seismically the Prupuh is a regionally recognised high amplitude event. Locally it is a downlap surface (Figure 18). The palaeoenvironmental and seismic criteria suggest the Prupuh is a maximum flood surface (Galloway, 1989). Repression of clastics caused a predominance of background pelagic foraminiferal sedimentation, and led to widespread deposition of clean bathyal limestone. A distinctive gamma ray minimum log response is recognised in most East Java wells (e.g. Figure 18). This is the reverse response to that seen in clastics-dominated basins, where flood surfaces are typically represented by GR maxima.

NEOGENE (MEGASEQUENCE III)

Plate Tectonic Setting

Collision of the Australian continent with a northerly island arc was initiated in the early Miocene (Figure 5). The interaction of the northerly moving Australian continent and the westerly motion of the Philippine Sea Plate is believed to result in the tectonic shaving process and resultant progressive collision of Australian microcontinental fragments within eastern Indonesia. The Buton microcontinent probably first interacted with Sulawesi in early Miocene (Davidson 1991) with major deformation in mid Miocene. The Banggai-Sula continental fragment collided with Sulawesi in the latest Miocene (Davis, 1990). Continued drive of the Australian continent to the north into the Sunda Trench and Banda Arc has resulted in thrust contraction and inversion along the arc. Major thrusts are interpreted to be located to the north of Flores, Lombok and Bali (Silver et al, 1983), with continued movement and seismic activity present-day. This is considered the principal driving mechanism of inversion in the East Java Sea.

Other possible controls on Neogene fault movement reversal in the East Java Sea are the compression resulting from blocking of the NW Borneo Trench in the late early Miocene and the Sulawesi collisions discussed above. However the proximity and scale of the westerly propagating Australian collision and parallelism of the main uplift axes with the Sunda Trench suggest that this is the dominant driving mechanism for inversion.

Structural Response (Basin Inversion)

The Prupuh Limestone effectively marks the seismic boundary between the Palaeogene extensional megasequence and the Neogene inversion megasequence. Early Miocene and younger uplift has affected a large area of the East Java Sea. This uplift has developed by episodic movement reversal on faults which had accommodated subsidence in the Palaeogene, some of which can also be seen to reactivate pre-Tertiary thrusts. The graben and half-graben which existed at early Miocene times have been inverted, resulting in reversal of the regional structural dip directions and sediment fill patterns which had existed prior to uplift. Detailed uplift history of individual faults is variable, although two main phases are recognised in the cast. Initial uplift commenced in early Miocene (N4/N5); marked broad scale changes in regional elevation resulted (Figures 11 & 12), as well as individual fault reversals. Further widespread uplift, both on partly inverted faults, and previously uninvited faults, occurred in mid Miocene (approx N11/N12).

A range of geometrical styles are observed which suggest reversal of motion on both planar and listric faults, by analogy with sand-box models (Buchanan and McClay 1991). The largest amplitude anticlinal structures within the East Java Sea exist along the
Inversion on the Sepanjang Fault produces the largest magnitude uplift in terms of both elevation and along-strike continuity within the East Java Sea. Degree of uplift along this major lineament has been sufficient to cause local crustal loading, and rapid foreland sedimentation in the Madura and Southern sub-basins. Other driving mechanisms for subsidence in these areas may include variation in plate convergence rate, the distribution and timing of magmatism, and the loading effect of possible northward translation of the volcanic arc. Uplift increases from east to west across cross-sections D to B (Figure 11 & 12). The observed uplift on the Sepanjang Fault zone can be explained by reversal of motion on the interpreted faults with local propagation of a thrust flat over the footwall block to the south, resulting in the development of hangingwall anticlines analogous to the fault-bend anticlines developed in thrust belt provinces. Further evidence of this style of deformation is provided by Figure 17 which displays evidence that the hangingwall overrides the footwall along a thrust flat. A combination of fault movement reversal and subsequent propagation of new thrusts, both as ramps (cutting across bedding) and flats (sub-parallel to bedding) within previously unfaul ted sequences are the principal mechanisms of achieving sufficient displacement to explain the observed structural elevation.

Inversion geometries of the axial rift areas are displayed on Figures 11 & 12. East of Kangean Island the uplift is broadly symmetric, and is interpreted to be a function of movement reversal on the Sakala and Sepanjang Faults (cross-sections A and B). Contraction in the footwall to the Sakala Fault has resulted in the formation of the Pagerungan anticline. The structural geometry along the northern flank of this symmetric uplift is controlled by movement reversal on the steeply dipping Sakala Fault Zone. Although substantial reverse motion has taken place, the Ngimbang Fm displays net-extensional offset across the Sakala Fault terrace on cross-section A. Along-strike to the east, on cross-section B (Figure 11), the Ngimbang Fm shows clear reverse fault geometries across the Sakala Fault terrace. Understanding this along-strike variation in structural style is dependent on gauging Palaeogene thickness variations in the hangingwall to the south of Sakala Fault. The observed inversion geometries can have resulted from a broadly consistent amount of reverse slip on the Sakala Fault Zone provided that the pre-existing Palaeogene normal dip-slip component increased from east to west (from cross-section B to A).

To the east of the Kangean Central Trough within the northern Lombok Basin a broadly symmetric uplift geometry appears to be controlled by the reactivation of pre-Tertiary thrusts. These faults had previously been reactivated in the Palaeogene as extensional faults. There is therefore excellent evidence for two periods of fault reactivation. This observation is critical to understanding the regional uplift geometries within the Lombok Basin which locally suggest inversion on listric faults, based on the observed asymmetric uplift geometry, and comparison with analogues. Reactivation of basement (Cretaceous) thrusts during Palaeogene extension provides a simple mechanism for the generation of a listric extensional fault profile. These are currently considered to be extremely rare features within basement except in cases of reactivation of pre-existing contractional structures.

In conclusion, the Neogene inversion history is most simply explained by fault movement reversal with the location of the major uplifts reflecting the location of the main Palaeogene depocentres, this being a function of the Palaeogene fault geometry and linkage. All the Neogene uplift structures currently interpreted can be explained by dominantly dip-slip reverse motion and subsidiary lateral motion on pre-existing Palaeogene structures, with local generation of new contractional faults.

**Stratigraphic Response**

Neogene inversion led to a reversal in basin geometry but not polarity (ie clastic sediment input remained from the west). During the Palaeogene sedimentation was concentrated in axial rift zones, with thinner sediment deposited on the relatively stable flanking platforms. Major reverse movement on the controlling faults led to the sediment thicks being inverted, and new Neogene depocentres forming to north and south of the inversion zone. These locally have a foreland basin geometry, notably in the Madura Strait and Kangean/Lombok Southern Basins, where locally over 6 seconds TWT of Neogene is developed. Reworking of
exposed parts of the inversion trend provided some of the sediment fill. In eastern areas the erosion products were largely mud-prone, whereas in the west some sands may have been reworked.

Despite the complex inversion history, the eustatic and sediment supply controls on Neogene basin fill can be resolved from the sequence stratigraphy of more stable areas, such as the northern platforms which remained net-extensional during the inversion phase. Three distinct Neogene units are recognised (Figure 13). Widespread early to mid Miocene highstand progradation; transgressive late Miocene terminated by an early Pliocene lowstand; and highly variable late Plio-Pleistocene sedimentation.

a). Early to mid Miocene (Sequence 50/55)

This unit is characterised on platformal areas by depositional systems which prograde and/or coarsen upward; these are clastic in the west and carbonate in the east. Age range is N5 to N13/14.

A well-imaged progradational system is observed on the Kangean northern platform (Figure 18). Well penetrations indicate that the system is entirely carbonate and calcareous muds. The system downlaps on to the N4/N5 Prupuh bathyal carbonates; progradation continues in several cycles up to late mid Miocene (approx N13). Microfaunal analysis indicates a significant percentage of planktonics throughout. This indicates progradation of a carbonate shelf margin or ramp, without development of platform top or reefal facies. Log responses are cyclic and do not indicate an overall cleaning upward, as would be expected in a progradational clastics system. The complete progradational sequence is interpreted as highstand deposition following the early Miocene flood. Several breaks in progradation are seen. One of these consists of a high amplitude, parallel seismic facies, the N10/11 Rancak limestone. Faunal content is shelfal to bathyal. It has a clean GR response, and may represent a flood event similar to the Prupuh pelagic carbonates.

Widespread progradation is also observed on the northern Lombok platform (Figure 19). Long-distance correlation to Doang-1 (Tyrrel, 1986) and seismic stratigraphic patterns suggest that the system is also carbonate. Correlation westward suggests that the prograding system is broadly the same age as the north Kangean carbonates. Several cycles of progradation/aggradation are well-imaged, above a downlap surface with local buildups. Much of the main carbonate platform has a rugose, high amplitude top surface. Seismic signal penetration is generally poor. These features are typical of karstified terrain. Locally a sigmoidal package is developed on the frontal progradational slope, which has a topset surface beneath that of the proceeding clinoforms, characteristic of a shelf margin or lowstand wedge.

The observations suggest that the termination of growth of the north Lombok carbonate system was due to exposure during a sea level fall. During the subsequent late Miocene transgression carbonates were unable to seed, (apart from isolated keep-up reefs), and the carbonate platform stepped back to its present position (approx the 200 m contour on Figure 20).

The equivalent early to mid Miocene of the western basin area and onshore East Java contains important sandstone reservoirs (Soetantri et al 1973). Three lithostratigraphic units are identified, the Tuban, Ngyarong and Wonocolo Fms. of N5 to N16 age, which overly the deepwater Prupuh Limestone. Their chronostratigraphic relationship is unclear. Locally onshore, seismic data indicate southeasterly progradation in the Ngyarong Fm. (Soeparyono, 1990) and so some degree of diachronity can be expected. First sand input is in the Tuban Fm (N6), and sand content increases upward; some coals are developed toward the top. Sands are thin, poor quality and laterally inextensive. The thicker sands of the Ngyarong Fm (approx N11) have been the main producer in the onshore East Java basin. The overlying mid to late Miocene Wonocolo Fm (N11 to N16) contains thinner, less continuous sands. Outcrop patterns indicate that structural growth occurred during this period. Coals are penetrated in the Bawean area offshore to the north, indicating probable backstepping of the coastal plain facies.

Onshore Madura Island, similar clastic cycles outcrop widely (Latief, 1990) in the Tawun and Ngyarong Fms of late early to mid Miocene age. Several cycles are logged, each capped by a carbonate. Faunal content suggests water depths decrease upwards.

The apparent southward limit of shallow marine and coastal plain facies, with local progradation, is marked by a prominent lineament, the Kujung fault zone (Figure 20). To the south of this the equivalent early to mid Miocene is in basinal facies, with thick mudstones, marl and pelagic limestones. Occasional sands are penetrated (eg Gigir-1, RRI 1986) which appear to be the deepwater equivalents of the Tuban and Ngyarong sands. Distribution is patchy.

The early to mid Miocene clastic depositional sequences on the platform areas north of the Kujung lineament show evidence of deposition during a sea level highstand, and are the equivalent of the Kangean/Lombok prograding carbonates. Clastics entered the system via
the Patiah and Central Troughs. Overall sand content decreases eastward, away from clastics supply. Minor carbonates which cap the elastic cycles on Madura island may represent minor transgressive floods during the progradational phase.

b). Late Miocene / Early Pliocene (Sequence 60/65)

This section is represented by generally monotonous mudstone and calcareous limestones over much of East Java Sea, with an important influx of clastics at the top. Age range is approximately N15-N20.

Sediment fill patterns were strongly controlled by topography produced during inversion. Inverted highs were eroded but reworked material was generally mud-prone. Reefal carbonates commonly fringe subaerial highs; an abundance of lithostratigraphic names are reported (summarised in RRI, 1986). In basinal areas winnowing of pelagic carbonates produced clean globigerinid grainstones which form porous and permeable reservoirs. (These carbonates may represent further flood events). The north Kangean and Lombok prograding carbonates were onlapped, suggesting a rise in relative sea level for this period. The late Miocene is transgressive overall, causing retreat of the shelf margin from its maximum basinward position in mid Miocene, leading to outer shelf/bathyal environments, and lack of progradation.

This seismic sequence is terminated by a widespread bevelling unconformity (T65; Figure 21) dated as early Pliocene. The crests of inversion structures were planed off, and the overlying strata are flat lying. In the Kangean northern platform and the Southern Basin (Figure 22), several sand units are deposited immediately below the unconformity. These are the first sands known to be deposited in eastern areas since the Eocene. Although there may have been some local reworking from inverted highs, several lines of evidence suggest that most sands are likely to have been derived from elastic sources on the exposed Sunda Shield to the west. The overall sand content of the basin in older sequences consistently increases westward, towards this elastic source. Transportation of coarse clastics from this area requires lowering of relative sea level to promote fluvial and shelf processes. This can be achieved either by reducing the accommodation space (sedimentation outpacing subsidence) or lowering absolute sea level, or a combination. In view of the prominent regional erosion a lowstand was the likely cause.

The effects of a sea level fall on the depositional patterns of the Java Sea are well documented in Ongkosongo, 1988. A 100 m fall would expose most of the shelf up to the eastern end of Java. The resulting incised river system would be similar to the submerged (Holocene) drainage pattern mapped on the Sunda Shelf (Figure 23). Confirmation of this process is the recovery of fine sands in seabed cores taken in 500 to 1000 m water depths in the Sakala Timur PSC. This model is proposed for the early Pliocene clastics; as with the modern examples, distribution of coarse clastic material would be controlled by the geomorphology of the exposed inversion ridges, and the position of new shelf edges.

Early Pliocene aged sands are described in the BD area of the Madura Strait (Widjonarko, 1990). Regional setting indicates these were deposited in a basinal environment. These are tentatively interpreted to be basin floor fans deposited during a lowstand, equivalent to the shelf clastics described above.

c). Plio-Pleistocene

Eustatic controls on this period (N21 to recent) are well documented. Rapid and large magnitude glacio-eustatic sea-level changes had a strong effect on shelf areas. In the East Java area, continued inversion and differential compaction is a further primary control on sedimentation. Seismic data show a complex structurally-controlled sequence stratigraphy. Numerous localised lithostratigraphic sequences are reported in these active areas (RRI, 1986). Stable shelves show the effects of repeated progradation and transgression. Although seismic data is locally good, well biostratigraphy is often poor in these tophole units. Minor production is reported onshore, but as this sequence is currently not a primary target in the East Java Sea the detailed sequence stratigraphy has not been attempted.

SUMMARY

The East Java Sea has evolved structurally in response to two major episodes of fault reactivation, in addition to the generation of new structures, following the accretion of the East Java Sea microplate in the late Cretaceous (Figure 24). The first phase of reactivation involved Palaeogene extension on pre-Tertiary thrusts which produced low-angle and locally listric extensional geometries. Elsewhere much steeper normal faults were developed due to the absence of pre-Tertiary contractional systems or on pre-Tertiary lineaments which cannot be imaged. The second phase of reactivation was during the Neogene inversion when all of the major Palaeogene faults experienced movement reversal, producing maximum uplift in the areas of pre-existing Palaeogene depocentres. Several structurally induced seismic boundaries of regional significance are recognised.
The most contentious structural issue concerns the relative importance of dip-slip and strike-slip components of movement during both phases of structural evolution described above. This has important implications for prospectivity, since different clastic fill patterns will result from different regimes. In cross-section the Palaeogene rifting produced a basin system which is dominated by fault-controlled subsidence, rather than a combination of extensional and contractional structures characteristic of strike-slip basins. However the isopach pattern and fault linkage in map view are not yet fully understood (although the latter may simply reflect inherited grain).

Palaeogene rifting within the East Java Sea must be evaluated regionally as part of the back-arc extensional system which fringed the SE Eurasian plate. The Palaeogene extension direction around this arcuate system may have varied due to the variable relative convergence vectors. A unique extension direction for the entire back-arc system is therefore considered unlikely. The observed variability of fault trends and the probable influence of inherited structural grain within the East Java Sea require that some faults will inevitably have experienced oblique-slip during the Palaeogene, irrespective of extension vector. As the precise extension vector for the East Java Sea is unlikely to have been perfectly orthogonal to the trend of the major faults, a transtensional (oblique-extensional) rift history is therefore proposed.

The Neogene uplifts are interpreted as the products of essentially orthogonal compression from the approximately northerly subducting Indian Ocean and northerly colliding Australian Plate; the inversion history is therefore interpreted as a dominantly dip-slip evolution. Partitioning of the shortening may have resulted in locally important wrench offsets, due to both the relative convergence vector not being perfectly orthogonal to the Java Trench at various periods during the Neogene, and also the variable orientations of Palaeogene faults.

The main point here is that although the Tertiary movement history of the major faults within the East Java Sea are likely to be resolved into components of major dip-slip and lesser strike-slip components, the basin is most simply interpreted as an inverted transtensional basin, rather than one which has rifted and closed in response to progressive crustal-scale wrench tectonics with consistent sense of shear from Palaeogene to present-day.

**Sequence Development and Petroleum Habitat**

Sediment fill in zones of extension and subsequent inversion is dominantly structurally controlled. Sequence interpretation requires prior structural restoration. Peripherial platform areas in contrast underwent net extension, with minor tectonism, and sediment fill patterns were primarily controlled by eustasy and basin position/sediment supply. Sediment is fines dominated as a result of basement type, which produced limited coarse clastics, and low palaeorelief also led to rapid coastline retreat during initial transgression. Initial deposition of clastics occurred in non-marine to marginal marine environments in a rift setting. Prediction of facies distribution in this primary fairway is limited by biostratigraphic and seismic resolution.

The bulk of the basin fill is marine, mixed carbonate and clastic. Highstand, lowstand and transgressive systems are recognised. Proportion of clastic to carbonate component depended on basin position, and relative magnitude of eustatic changes. The East Java Basin provides excellent examples of the comparative response of clastics and carbonate depositional systems to eustatic controls.

Relative highstands led to both carbonate and clastics progradation depending on basin position, with the later being proven targets. Relative sea level falls caused major shifts in facies belts. During major lowstands clastics became predominant as fluvial systems covered more of the exposed shelf and carbonate platforms were exposed and growth halted. Coarse clastics deposited in previously basinal areas during sea level lowstands represent a significant exploration target.

Transgressive periods led to repression of coarse clastics input and limited clastic reservoir potential. Carbonates responded to transgression by strong vertical growth, forming significant reefal targets in basinal areas. Subsequent maximum flood surfaces at the peak of transgression are the best correlative events recognised both from seismic and well data. Clean pelagic carbonates formed during floods by repression of clay input locally have good reservoir characteristics.

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REFERENCES


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ADDITIONAL DATA FROM: HAMILTON (1979), HASAN (1991)

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