ABSTRACT

Java has an apparently simple structure in which the east-west physiographic zones broadly correspond to structural zones. In the north there is the margin of the Sunda Shelf, and to the south of the shelf are Cenozoic volcanic arc rocks produced by episodes of subduction-related magmatism. This simplicity is complicated by structures inherited from Cretaceous subduction beneath Java, by extension and subsidence related to development of the volcanic arcs, by late Cenozoic contraction, and by cross-arc extensional faults which are active today. During the Paleogene arc volcanoes acted as a load which caused a flexural basin to develop between the Sunda Shelf and the Southern Mountains Arc which can be traced from West to East Java. The basins contain quartzose clastic and volcanic debris derived from north and south. Based on field observations in different parts of Java we suggest that major thrusting in southern Java has displaced the Paleogene volcanic arc rocks northwards by more than 50 km and eliminated the flexural basin in West Java. The amount of thrusting diminishes from West to East Java. We suggest Java can be separated into three distinct structural sectors which broadly correspond to the regions of West, Central and East Java. Central Java displays the deepest structural levels of a series of north-directed thrusts, and Cretaceous basement is exposed; the overthrust volcanic arc has been largely removed by erosion. In West and East Java the overthrust volcanic arc is still preserved. In West Java the arc is now thrust onto shelf sequences that formed on the Sundaland continental margin. In East Java the volcanic arc is thrust onto a thick volcanic/sedimentary sequence formed north of the arc in a flexural basin due largely to volcanic arc loading. Structural and stratigraphic traps beneath the overthrust arc offer new hydrocarbon exploration possibilities, particularly in West Java.

INTRODUCTION

Java (Figure 1) is one of the many islands at the Eurasian margin in Indonesia in which subduction has been an important influence on its geological history. Subduction is active today all round the SE Asian archipelago, from Sumatra to the Philippines, and has been almost continuous for much of the Cenozoic, particularly in Indonesia. Sumatra and the Philippines, where subduction is oblique, are characterised by features such as major strike-slip faults, displaced and fragmented terranes, and bends in faults that may be associated with sedimentary basins or folding and thrusting, depending on the geometry of the bend. Volcanic activity is also often localised at fault bends or tips, and complexities in volcanic activity with time have been interpreted to result from oblique subduction of major features on the downgoing slab such as fractures or ridges, or tearing of the subducting slab opening slab windows causing seismic gaps or anomalous heat flows. Overall, it is reasonable to expect oblique subduction to produce a complex geology as features migrate along subduction margins.

In contrast, Java is often cited as an example of the product of orthogonal subduction and the volcanic island appears to have a relatively simple structure. The physiographic zones recognised by van Bemmelen (1949) were identified by him as structural units, and they are broadly parallel to the east-west elongation of the island and the strike of the subduction trench south of Java. He recognised some deformation on Java, and although it is sometimes difficult to interpret his ideas in terms of modern tectonic processes, van Bemmelen evidently saw deformation as predominantly vertical responses to magmatic growth of geanticlinal features, which could result in thrusting
and folding due to gravity-driven movements. He considered that the Sunda mountain system was typified by outward migration of orogenic deformation with time, said by him to be seen clearly in Sumatra. However, according to van Bemmelen, Java showed a contrary inward migration of deformation from the Indian Ocean, which he appears to attribute (e.g. van Bemmelen, 1949, page 658) to deep crustal or mantle processes associated with volcanic activity. The main episode of deformation he identified, which did produce “northward folding and thrusts” in north Java “had the character of backward- or hinterland folding”.

The idea that Java lacks significant deformation has been passed down from van Bemmelen, and major thrusts are not shown on most geological maps, except in north Java. Simandjuntak and Barber (1996) interpret a major backthrust, the Barabise-Kendeng thrust, to run the length of the island and report that some segments are currently active. They interpret there to have been “a change from an extensional to a compressional regime across the subduction system” and suggest this could be a consequence of subduction of features such as the Roo Rise on the Indian Plate (Figure 1), or that localisation of compression may be due to magmatic intrusion and consequent uplift of the arc. This suggestion implies that the northward thrusting in north Java is part of contractional deformation of a large wedge north of the trench, with compression between the trench and a backstop. The reason for a backstop in north Java is not clear; usually in arcs, the interpreted backstop is between the arc and the trench, not behind the arc. The concept of such a large wedge is also unusual, and suggests that the entire block is being pushed northward, with deformation localised at its northern margin.

Oil company geologists in Indonesia are very familiar with the significant thrusting in north Java, and with a few exceptions this represents the southern limit of extensive subsurface exploration which has been mainly offshore north of the island. The subsurface structure of the island, and certainly the crust south of the island, is less well known, because of problems with exposure, difficulties in mapping structures at the surface, and the paucity of seismic data. However, as a result of our fieldwork on Java in the last few years we suggest that there is more thrusting than previously recognised, which is of great importance in understanding the structure of the arc, and may be of interest to exploration geologists investigating frontier plays. In this paper we identify important features which we suggest are better explained by a thrust model for Java. We propose that Paleogene arc rocks have been thrust northwards towards the Sunda Shelf and that a modern analogue of the Eocene to Early Miocene sedimentary and tectonic setting is found at the present day in the East Java-Bali region. We first discuss West Java, and then discuss thrusting and related deformation from other parts of Java, and finally consider briefly the implications for hydrocarbon exploration.

**WEST JAVA**

The Ciletuh-Bayah area (Figure 2) contains key features which we consider make the case for thrusting in southern Java most clearly. We therefore first summarise the geology of the area, and then discuss previous and new interpretations, followed by briefer descriptions of examples of thrusting and deformation in other parts of West Java.

**Ciletuh-Bayah**

The Ciletuh area (Figure 2) is well known for its exposures of the oldest rocks in West Java, which include rocks interpreted to be Mesozoic. The “Pre-Tertiary” of Ciletuh Bay was reported by van Bemmelen (1949) to consist of “metamorphic basic and ultra-basic rocks (gabbro, peridotite, serpentine) with chloritic schists and phyllites”. Schiller et al. (1991) described an ophiolitic assemblage of peridotites, gabbros, pillow lava basalts and serpentinites associated with greenschists, micaschists, amphibolite schists and quartzites, which has often been interpreted as a tectonic melange (e.g. Parkinson et al., 1998; Martodjojo et al., 1978; Endang Thayyib et al., 1977). Little is known about the ages of these rocks. Schiller et al. (1991) reported that radiometric dating using the K-Ar method yielded very few conclusive results due to alteration. A pebble of basalt from a conglomerate of the Ciletuh Formation yielded a Late Cretaceous age, whereas plagioclase and whole rock ages from a gabbro gave Paleocene to Middle Eocene ages. By comparison with the Lok Ulo complex of Central Java (Parkinson et al., 1998), a Cretaceous age for the ophiolitic rocks is likely.

The Middle and possibly Upper Eocene rocks of the Ciletuh area have been assigned to the Ciletuh Formation, between 400 and 1500 m thick, and are generally regarded as having been deposited on Cretaceous basement (van Bemmelen, 1949; Marks, 1957; Martodjojo et al., 1978; Schiller et al., 1991; Sukamto, 1975; Endang Thayyib et al., 1977). Most authors have interpreted the contact to be
unconformable, although Martodjojo et al. (1978) suggested that the Ciletuh Formation rested conformably on the melange complex and van Bemmelen reported local thrust contacts between the pre-Tertiary and the Ciletuh Formation. The Ciletuh Formation has been separated into two main lithofacies (Marks, 1957; Schiller et al., 1991; Sukamto, 1975; van Bemmelen, 1949). The Pre-Tertiary rocks are “unconformably and transgressively covered by the Eocene: sandstones and conglomerates with boulders of the Pre-Tertiary, mudstones, breccias and graywackes” (van Bemmelen, 1949). Schiller et al. (1991) described “a quartzose lithofacies composed of mostly quartz and a wide variety of lithic rock fragments; and a less pervasive volcanic lithofacies composed entirely of volcanioclastic sediments”. The rocks of the Ciletuh Formation were suggested by van Bemmelen (1949) to be shallow marine deposits but Schiller et al. (1991) reinterpreted them as a sand-dominated submarine fan deposited in deep water in a forearc or interarc position.

About 20 kilometres northwest of Ciletuh in the Bayah area there is more than 1000 m of Eocene quartzose conglomerates, sandstones and mudstones of the Bayah Formation (Koolhoven, 1933; Sukarna et al., 1993) divided into a southern and northern facies. The southern facies is predominantly conglomerates and sandstones, and van Bemmelen (1949) remarked on its similarity to the Ciletuh quartzose lithofacies. The northern facies, or Cipageur Member (Sukarna et al., 1993), consists of clays and quartz sandstones with intercalated limestones of Early to Middle Eocene age (Koolhoven, 1933). The Bayah Formation is interpreted as fluvio-deltaic and shallow marine deposits; van Bemmelen (1949) also noted the presence of some tuff intercalations. Schiller et al. (1991) suggested the Bayah Formation is a shallow water equivalent of the Ciletuh Formation. Koolhoven (1933) noted that “a few observations strongly favour equal age” although van Bemmelen (1949) observed that the southern facies of the Bayah Formation is probably younger.

Just west of Bayah, between the Cimadur and Cidikit Rivers, the Upper Eocene Cicarucup Formation is exposed in the cores of anticlines (Sukarna et al., 1993). Its thickness was estimated by Koolhoven (1933) to be at least 400 m although this is uncertain because of faulting and folding (Sukarna et al., 1993). The formation includes andesitic conglomerates, quartz sandstones, clays, limestones and thick tuff units deposited in a littoral to shallow marine environment (Koolhoven, 1933; Sukarna et al., 1993). Koolhoven (1933) suggested that the formation indicated that West Java was largely emergent in the Late Eocene, in contrast to the Middle Eocene, and van Bemmelen (1949) observed that andesitic detritus indicated that volcanic activity had begun in this part of West Java earlier than elsewhere in Java.

In the Ciletuh area, the Ciletuh Formation is overlain by volcanic rocks of the Jampang Formation which are part of the “Old Andesites” of Dutch workers. The formation is considered to be Lower Miocene based on biostratigraphic analysis of limestone lenses in the formation (Sukamto, 1975) and was estimated by Dutch workers (e.g. Verbeek and Fenema, 1896; Koolhoven, 1933) to be up to 5 km thick. There must therefore be a major break as the Upper Eocene and Oligocene is missing. The formation consists largely of basaltic to dacitic volcanic breccias, tuffs and lavas. In the Ciletuh area the Jampang Formation forms a dramatic amphitheatre with steep sided cliffs, particularly along the northern boundary, up to 500 m high, surrounding a window of the older Ciletuh and Ciemas (Clements and Hall, 2007) Formations. Close to the coast at Ciletuh Bay are well bedded tuffs and breccio-conglomerates several metres thick, which are predominantly basaltic andesites and andesites. These types of rock are common in the Southern Mountains of West Java and represent the most proximal deposits of the ‘old volcanic arc’ (van Bemmelen, 1949) and must have been deposited relatively close to the volcanic centres. Thus, for the Early Miocene, the position of the volcanic arc is known; for earlier times it is less clear.

**Interpretation of the Ciletuh-Bayah region**

All explanations of the geological relationships in the Ciletuh-Bayah area of West Java are essentially stratigraphic and autochthonous. Schiller et al. (1991) give a clearly illustrated explanation of the Eocene, shown in Figure 3. They suggested the quartz-rich material of the Bayah and Ciletuh Formations was derived from a Sundaland continental source to the north. They interpreted the Bayah Formation as shelf edge deposits and their Ciletuh Formation as a sand-dominated submarine fan deposited in deeper water to the south in a forearc or interarc position. The Ciletuh amphitheatre is therefore an inlier with Eocene and older rocks in the centre, overlain unconformably by the Miocene Jampang Formation.

Our observations suggest a number of problems with the autochthonous interpretation. For the
Middle Eocene the character of the two lithofacies in the Ciletuh Formation is quite different. One is quartz-dominated and the other is composed of volcaniclastic debris. There is no transition observed between the two lithologies and in the Ciletuh area, where the two lithofacies are found close to one another in outcrop, there is no sign of mixing of quartz-rich and volcaniclastic material. For this reason we assign the two lithofacies to different formations (Clements and Hall, 2007): a volcaniclastic Ciletuh Formation and a quartz-rich Ciemas Formation. The material in the Ciletuh Formation is almost all derived from ophiolitic basement, or volcaniclastic sources, with rare epidote amphibolites and shallow marine limestones; quartzose material is typically chert fragments and no material resembling the quartz of the Ciemas Formation is seen. Blocks of Nummulites limestones, and some volcaniclastic sandstones, were incorporated when incompletely lithified and show soft sediment deformation typical of rapidly slumped material. In the interpreted submarine fan of Schiller et al. (1991) not only is the most distal material completely different from the supposed source and more proximal material, it is also the coarsest (blocks up to 10 m across) and is highly angular.

We suggest these two formations are best interpreted as contemporary but deposited in separate settings (Figure 3). The Ciemas Formation, as suggested by Schiller et al. (1991), does represent a transition from shelf-slope to deeper water fan. Quartz-dominated material was derived from the Sundaland continent to the north, and deposited by rivers flowing south on the coastal margin as the fluvi-marine Bayah Formation; some material was transported into deeper water down a steep slope into the submarine fan of the Ciemas Formation. Much further south in the forearc was the site of formation and deposition of the volcaniclastic Ciletuh Formation. Many features of the formation indicate active tectonism. The size and angularity of blocks require steep submarine fault scarps, exposing basement, down which was carried partly lithified volcaniclastic material and rare shallow marine limestones as debris flows, into a rift in which basaltic lavas were erupting. The association of deep marine deposits, active faulting of basement and steep slopes, accompanied by volcanic activity, slumping and syn-sedimentary deformation is best interpreted as due to extension in a deep marine forearc setting accompanying the onset of subduction and the initiation of the volcanic arc. Such features can be observed today in places such as Tonga, or the Izu-Bonin-Marianas arcs.

The original large distance between the Ciemas and Ciletuh Formations is now reduced to zero. We interpret the juxtaposition to be the result of major northward thrusting of the Southern Mountains arc. We suggest the thrust front follows the northern edge of the Jampang Formation along the Cimandiri Valley (Figure 2). In the Ciletuh area, the contact between the Jampang Formation and the underlying Ciletuh Formation is a thrust and the amphitheatre is therefore not an inlier but a thrust window.

We suggest that the thrust hypothesis offers a simpler explanation of apparent stratigraphic complexities requiring large vertical movements and relative sea level changes. The field relationships can be explained assuming normal stratigraphic contacts, unconformities and special arguments about sediment distribution but in our view they require some unlikely patterns of uplift and subsidence. For example, the absence of the Upper Eocene and Oligocene at Ciletuh can be explained if the area was elevated in the Late Eocene and became a structural high on which no rocks were deposited. This would require a rapid emergence from several kilometres water depth and a major tectonic event. There is no evidence on seismic lines a short distance to the west in the offshore Malingping block (Keetley et al., 1997; Yulianto et al., 2007) for such an event. Indeed, less than 20 kilometres to the north of Ciletuh, in the Bayah area, there is a thick sequence of Upper Eocene shallow marine quartz-rich clastic rocks implying continued subsidence. If the Ciletuh block was a rapidly elevated topographic high, it would have been a source of sediment, yet there is almost no sign of Ciletuh-derived sediment in the Bayah Formation, and relatively small amounts of volcaniclastic or basement material is present in Oligocene formations north of the Cimandiri River. In most of West Java the Oligocene rocks north of the Cimandiri River are quartz-rich clastic deposits derived from the north.

The character of the Jampang Formation indicates a calcalkaline arc, suggesting a prolonged period of volcanism evolving from the deep water basalts of the Middle Eocene Ciletuh Formation to the largely emergent andesites and pyroclastics of the Jampang Formation. The apparent absence of Upper Eocene and Oligocene volcanic material has led to suggestions that volcanic activity, and possibly subduction, did not begin until the Late Oligocene (e.g. Hamilton, 1988) although, as noted above, van Bemmelen (1949) observed that volcanic activity had begun in the Bayah area “in the lower part of the Paleogene, that is earlier than in the rest of
Java”. We suggest that the paucity of volcanic debris to the north was in part because during most of the Paleogene the Southern Mountains arc in West Java was submerged, relatively non-explosive, but most important, relatively distant from the Bayah area and Cimandiri Valley. The Southern Mountains Arc and the shelf sequences dominated by quartzose Sundaland-derived material were originally separated by tens of kilometres rather than the few kilometres of the present-day, and have been brought closer together or juxtaposed by northward thrusting.

DEFORMATION ELSEWHERE IN SOUTH JAVA: WEST JAVA

Bayah region

Over much of the Bayah region steep dips and repetition of lithologies due to faulting is common. Along the south coast from Bayah towards Malingping Upper Eocene quartz-rich sandstones of the Bayah Formation dip at low angles along much of the coastal section. A short distance inland dips commonly change and bedding is sub-vertical and strikes broadly E-W. The upper part of the Bayah Formation consists of quartz-rich sandstones, pebbly sandstones and rare conglomerates with coals and carbonaceous mudstones. These Eocene coals are worked locally but operations are always small because of consistently steep dips (>40°), and discontinuity of coals, some of which is due to thrusting (Ziegler, 1916). Oligocene coals of the Cimandiri and Cikarang coal fields in the Bayah region are part of the Cijengkol Formation have similar steep dips and are located within asymmetric anticlines and synclines which verge toward the north.

The Cijengkol Formation is best seen along the Ciapus River, to the north of Bayah, where there are steeply dipping turbidites, algal and reefal limestones, calcareous sandstones and reworked limestones which contain coral fragments, foraminifera and lithic clasts, grey mudstones, quartz-rich sandstones and coralline limestones. Some of these lithologies are separated by faults and many dip at more than 30°.

Cimandiri Valley, Cikalong Formation

Lower Oligocene clastic sedimentary rocks are exposed over an area of several square kilometres southwest of Sukabumi near the village of Warungkiera. They were assigned to the Rajamandala Formation by Sukamto (1975) and the Ciletuh Formation by Kusumahbrata (1994); we assign them to the Cikalong Formation (Clements and Hall, 2007). There are pebbly conglomerates with highly rounded pebbles up to 3 cm long, bedded quartz-rich sandstones, calcareous sandstones and limestones, tuffaceous sandstones and dark mudstones. Channels, load casts, normal grading and fluid escape structures suggest rapid deposition. There are several hundred metres of sediments although observed structural repetition by folding and faulting means that thickness estimates are uncertain. The rocks are deformed and throughout the area bedding dips are consistently greater than 60°; along the Cimandiri River quartz-rich sandstones and mudstones strike approximately 055°.

Similar rocks are exposed further east, to the south of Cianjur and at Padalarang. At these localities the Cikalong Formation lies beneath folded Oligo-Miocene limestones of the Rajamandala Formation, in anticlinal cores (see below). Rare limestone olistoliths are present both at Cikalong and in the Cisukarama valley, south of Cianjur. These are typically coralline limestones with abundant foraminifera of similar age to the Cikalong Formation (P. Lunt, pers. comm., 2006). The presence of agglutinated foraminifera in Cikalong Formation mudstones (P. Lunt, pers. comm., 2006) suggests a deep water environment. We suggest that the shallow water limestones were transported as olistoliths into deeper water down a steep slope south of a narrow shelf.

Cikalong Formation rocks are exposed along the line of the Cimandiri Fault which extends from Pelabuhanratu to Bandung (Dardji et al. 1994; Martodjojo, 1984, 2003; Schiller et al., 1991). This is also the northern edge of the Oligo-Miocene Jampang Formation and a steep scarp of Southern Mountains volcanic rocks rises abruptly from the southern bank of the Cimandiri River. Different structural interpretations of the mapped relationships across the Cimandiri Valley are shown in Figure 4. The line of the valley has been interpreted as a strike-slip fault (Dardji et al. 1994) that influenced sedimentation in the Eocene and/or Oligocene (Martodjojo, 1984, 2003; Schiller et al., 1991). It is often said to be an active strike-slip fault and has been traced offshore (Schluter et al., 2002; Susilohadi et al., 2005) although on SRTM images it does not have the sharp linear character of strike-slip faults such as the Palu-Koro Fault in Sulawesi or the Sumatran Fault Zone. We suggest it is a thrust, and is not an active fault. The field relationships in the Cimandiri Valley are ambiguous.
and can be interpreted to indicate Early Miocene thrusting or post-Middle Miocene thrusting (Figure 4).

Rajamandala Ridge

The Rajamandala Formation includes shallow marine algal, reefal and reworked reefal limestones with abundant shell, coral and foraminiferal material of Late Oligocene to Early Miocene age (Baumann et al., 1973; Carnell, 2000; M. BouDagher-Fadel, pers. comm., 2006). The limestones form a prominent ridge that can be traced ENE-WSW from just west of Bandung to the south of Cianjur where the ridge terminates and the limestones disappear under younger rocks. Similar limestones along strike in the Sukabumi area are generally accepted to be a continuation of the Rajamandala Formation. The limestones dip steeply and are tightly folded in the Rajamandala area west of Bandung; the major fold is overturned to the north and the northern limb is locally thrust northwards over younger rocks (Figure 5). The ridge was described by van Bemmelen (1949) as a steep anticline or anticlinorium overturned to the north, and he reported that the core of Oligocene flysch has been squeezed out diapirically on the road to Cianjur to form a northward overthrust. In places elsewhere, the structure may be more complicated, with low dips on the limestones, but generally dips are steep, folds verge towards the NW and there is thrusting of Rajamandala Limestone over the Citarum Formation towards the NW.

Cimapag Formation

On the south coast between Tanjung Layar and Ujung Lengonwaru the Tuff Member of the Cimapag Formation (Sujatmiko and Santosa, 1992) is well exposed. The Cimapag Formation is the equivalent of the Jampang Formation (Sujatmiko and Santosa, 1992) is well exposed. The Cimapag Formation is the equivalent of the Jampang Formation in the Southern Mountains. At Tanjung Layar there is a spectacular coastal section with 100m of bedded units exposed in small cliffs and the modern wave-cut platform. At the base of the section are well bedded volcaniclastic sediments which are typically laterally discontinuous and channelised. There are many conglomeratic debris flows which contain clasts of tuffaceous sandstones, calcareous sandstones, and large boulders of basalt that appear to have been dumped into finer material. The sandstones are cross bedded, have scoured bases with load casts and contain abundant plant and charcoal fragments up to several centimetres long, and common vertical and horizontal burrows. There are many features indicating rapid deposition, perhaps as lahars. These rocks pass up into a number of thickly bedded ignimbrites. These are 10-15m thick and typically have a breccio-conglomeratic pumice-rich basal unit with an erosional base, containing some reworked angular lithic, and well rounded siliciclastic and calcareous clasts up to 40cm across. The ignimbrites grade up into several metres of finer block and ash material with diffuse lamination which in turn grade into several metres of fine ash with very fine convolute lamination. Spectacular flame structures seen in the unit indicate the direction of transport was broadly to the west. The rocks are pyroclastic flow deposits, overlain by ash fall layers which were later deformed by products of subsequent explosive events; there are at least four of these events recorded at Tanjung Layar. These rocks have been deformed since the Early Miocene since they are now sub-vertical and strike east-west parallel to the coast.

DEFORMATION ELSEWHERE IN SOUTH JAVA: EAST JAVA

In the southern part of East Java the case for northward thrusting is less obvious than West Java. The Eocene to Miocene arc rocks of the Southern Mountains are relatively well exposed, but the equivalent age rocks to the north are generally not exposed, nor are the contacts between them and the Southern Mountains Arc. The structure and stratigraphy of East Java appears relatively simple (Smyth et al., 2005, 2007a). In the north the southern edge of the Paleogene Sunda Shelf can be traced from west to east along the Rembang Hills where there is now a northward-vergent fold and thrust belt. To the south of the shelf was the Kendeng Basin, largely filled with the Eocene to Miocene volcaniclastic products of the Southern Mountains Arc, which was situated south of the basin. The Kendeng Basin is very poorly exposed, and there is little subsurface information, but the basin sequence is interpreted to thicken southwards towards the Southern Mountains (Pertamina, 1996). The physiographic trough of the Kendeng Basin deepened towards the south during the Paleogene. Today, the rocks of the Southern Mountains Arc dip at a low angle southwards and their northern contact with the Kendeng Basin is not exposed. Previously we have interpreted the structure of the Southern Mountains Arc and southern Kendeng Basin to be a largely undeformed stratigraphic transition from basin to arc (Smyth, 2005; Smyth et al., 2005, 2007a), simply tilted to the south as the result of the uplift and emergence of East Java, although the
Pertamina (1996) cross section shows thrusting at this contact. There are two locations near the northern edge of the Southern Mountains that support a thrust interpretation.

**Prigi**

In the Southern Mountains around Prigi are carbonate rocks of the Lower Miocene Campurdarat Formation, volcanic rocks of the Mandalika Formation and many small hills which are small andesite intrusions (Samodra et al., 1992a, b; Rahardjo et al., 1995). In a small quarry near Prigi, about 5 km from the nearest outcrop of the Campurdarat Formation, there are black limestones with volcaniclastic interbeds assigned to the Prigi Member of the Campurdarat Formation (Smyth, 2005) exposed in a small quarry. The limestones contain volcaniclastic debris as well as a diverse faunal assemblage including corals, red algae, ostracods, echinoid spines and benthic foraminifera indicating a Middle Miocene (N8) age. They are interbedded with graded crystal-lithic volcaniclastic sandstones with scoured bases and tuffaceous muds which show evidence of slumping and dewatering. These rocks are interpreted as deposited close to an active volcanic source, where volcanic debris was mixed with shallow marine bioclasts on a narrow shelf, with debris flows carrying all this material downslope. What is unusual is the strongly deformed character of these rocks (Figure 6). Nearby exposures of the Mandalika Formation and the Campurdarat Formation are undeformed and dip gently towards the south. In contrast, in the Prigi Quarry the beds are tightly folded, with overturned axial planes dipping eastwards, and folds plunging at a low angle towards the northwest. No such folding has been seen elsewhere. It could be explained by deformation at or near a thrust at the base of the Southern Mountains Arc.

**Wonosari**

At the eastern end of the Southern Mountains is an extensive area of limestones, modern karst and caves in the Wonosari Hills to the south of the Jiwo Hills and Batu Agung Escarpment (Figure 7). The Upper Oligocene to Lower Miocene volcanic rocks of the Batu Agung Escarpment were deposited in a subaerial to shallow marine setting. Volcanic activity culminated in a major explosive eruptive phase (Smyth et al., 2005, 2007a) at about 20 Ma, and then ceased for about 10 Ma. During the period when there was little or no volcanic activity the Lower to Middle Miocene Sambipitu, Kepek and Wonosari Formations were deposited unconformably on the volcanic rocks of the Batu Agung Group (Smyth, 2005). The Sambipitu, Kepek and Wonosari Formations dip at less than 10° towards the south, much less steeply than the underlying volcanic rocks of the Batu Agung Group (25-35°).

The Sambipitu and Kepek Formations interdigitate and are interpreted as the deposits of the ‘Wonosari Trough’ (Lokier, 2000a,b). This trough is suggested to have been a narrow (5-10 km wide and 45 km long), deep basin (~1 km) bounded to the north by the Batu Agung Group volcanics, and to the south by a fault-bounded block on which the platform carbonates of the Wonosari Formation were deposited (Lokier, 2000a,b). The carbonate platform supplied abundant material to the Kepek Formation, a sequence of turbidites containing redeposited carbonate debris and volcaniclastic material, on its northern flank. To the north of this was the Sambipitu Formation, a series of calcareous volcanogenic turbidites, that now occupies the area of low topographic relief of the northern Wonosari Plain, south of the Batu Agung Escarpment. These rocks have more volcanic debris, less carbonate, and have a more distal character than the Kepek Formation.

There are some problems with this simple stratigraphic interpretation. The southern side of the Wonosari Trough is preserved and there is a transition to the Wonosari Platform, but on the north side of the trough there is no obvious transition from the deep water deposits of the Sambipitu Formation to the eroding volcanic source area inferred to the north. The Kepek and Sambipitu Formations record a significant increase in water depth at the site of the previously emergent Early Miocene arc. The dimensions of the Wonosari Trough imply rapid localised subsidence immediately south of the arc following the cessation of arc activity. For its depth the trough is exceptionally narrow, and although there are deep elongate basins in the present-day Java forearc (Kopp et al., 2002; van der Werff, 1996) they are much wider.

These problems could be explained if the Wonosari Platform has been thrust northwards (Figure 7), stacking the underlying Kepek and Sambipitu Formations, and reducing the apparent width of the basin. This interpretation is consistent with the structure of the area, with thrusts parallel to the low dips of the sediments, but would be difficult to prove without very detailed dating. Biostratigraphic studies are hampered by diagenetic alteration of
carbonate-rich lithologies, lack of critical age-diagnostic faunas, and faunal reworking.

DEFORMATION ELSEWHERE IN SOUTH JAVA: CENTRAL JAVA

Central Java includes the most extensive area of basement rocks known in Java, the Lok Ulo Complex (van Bemmelen, 1949; Asikin et al., 1992). This is usually regarded as the imbricated product of Cretaceous deformation (e.g. Parkinson et al., 1998; Wakita et al., 2000) at a subduction margin that extended from West Java, through the Lok Ulo Complex, to the Meratus Mountains. Parkinson et al. (1998) suggested that subduction ceased in the Cretaceous after collision of a Gondwana continental fragment that is now beneath most of West Sulawesi. In contrast, Sribudiyani et al. (2003) suggested that subduction ceased from the Cretaceous to the Eocene. They proposed that there is a continental fragment beneath most of East Java that collided with a volcanic arc, represented by the Jatibarang Formation, at the end of the Eocene, and they interpret the Karangsambung Formation and associated rocks that overlie the Lok Ulo Complex as forearc deposits. Northward thrusting and largely north-vergent folds are known from the Karangsambung region (Figure 8). Thrusts cut Middle Miocene strata and Miocene and Pliocene formations are folded (Asikin et al., 1992) suggesting some important deformation is young.

We too consider there is Gondwana crust beneath parts of East Java, and dating of recycled zircons (Smyth et al., 2005, 2007b) indicates that there is a continental crust beneath the Southern Mountains that extends west almost to Yogyakarta. However, like Parkinson et al. (1998) we suggest this fragment collided in the Cretaceous and terminated subduction (Smyth et al., 2007b). In East Java the oldest Cenozoic sedimentary rocks above basement, in the Nanggulan area, are fluvialite quartzose conglomerates and sandstones lacking volcanic debris, and it is difficult to reconcile such a terrestrial fluvialite setting with a deep forearc basin a short distance to the west in the Karangsambung area. This would require a trench to be situated in Central Java along strike from a volcanic arc in the Southern Mountains. In marked contrast to West and East Java, in Central Java there are no Southern Mountains and the Paleogene arc rocks are absent.

In East Java, the Eocene terrestrial rocks pass rapidly up into volcanioclastic-rich marine deposits indicating a deepening basin to the north of the Southern Mountains Arc, the Kendeng Trough. In Central Java, the Eocene-Oligocene Karangsambung and Totogan Formations are also deep water deposits, and include scaly clays with Nummulites limestone blocks, polymict conglomerates and basalt blocks, interpreted as olistostromes (A.H. Harsolumakso, pers. comm., 2005). However, in contrast to similar age rocks further east, they do not contain abundant volcanic material but do contain large amounts of debris derived from continental sources. The stratigraphic observations in East and Central Java can be reconciled if the Karangsambung rocks were deposited in a deep basin that was the western continuation of the Kendeng Trough, but supplied with sediment derived largely from the Sunda Shelf to the north, whereas in East Java the Kendeng Trough was supplied with debris derived predominantly from the arc to the south, the Southern Mountains Arc. The Kendeng Trough was a flexural response to volcanic loading by the Southern Mountains Arc (Smyth et al., 2005; Waltham et al., 2007) which raises the question of where is the arc that produced the flexural basin in Central Java. We suggest it was there, and was later thrust northwards, but has been removed by erosion. Central Java exposes a deeper structural level than either East or West Java; the upper thrust sheet of the volcanic arc has been removed and now exposes the rocks of the deep marine trough, and the underlying basement (Figure 9).

DISCUSSION

Modern analogue

A model for the Eocene to Early Miocene setting is found at the present day in the East Java-Bali region. Figure 10 illustrates the key features. To the north is the Sunda Shelf which during periods of low sea levels in the Pleistocene has been an area of large rivers carrying sediment from south Borneo and Java towards the east and southeast. At the shelf edge are the islands of Madura and Kangean, and shallow water reefs distributed between them. During periods of low sea level these carbonates are likely to be reduced in area, and possibly destroyed, whereas in periods of highstands they become more widespread.

Immediately to the south of the shelf edge is an elongate basin oriented west-east. South of Madura the basin is almost full of Plio-Pleistocene sediments (Pertamina, 1996), but to the east, north
of Bali, the basin contains much less sediment and is up to 1.5 km deep, with very steep slopes to the north and south. This basin extends to the east north of Bali and Lombok where it is an unfilled physiographic trough with depths up to about 1.5 km. The basin is up to 100 km wide and can be traced along the arc for at least 500 km. South of the basin and trough are the volcanoes of East Java, Bali and Lombok. We suggest this feature is the equivalent of the Eocene to Miocene Kendeng Trough in East Java, i.e. a flexural response to volcanic arc loading to the south. The basin runs parallel to the arc and has relatively steep northern and southern slopes. To the south is a very narrow shelf adjacent to the volcanoes of Bali and Lombok.

During periods of explosive volcanic activity volcanic debris would be fed rapidly into the basin to the north as debris flows and turbidites. South of Madura it is likely that the basin was filled from the west by debris carried by rivers draining East Java, from the south by volcanic debris derived straight offshore from the volcanoes, and from the north by carbonate carried downslope from Madura; the majority of the basin fill is likely to be reworked volcanic material. The basin fill is likely to be very similar to the fill of the Eocene to Miocene Kendeng Basin north of the Southern Mountains Arc.

On the north side of the basin is the wide shallow marine Sunda Shelf. During periods of highstands, such as the present-day, much of the sediment carried downslope into the basin is probably carbonate derived from the islands such as Kangean and Madura and the carbonate reefs between the islands. During periods of lowstands, such as the Last Glacial Maximum, most of the shelf would have been emergent and there would have been much more quartzose continental clastic material carried by rivers, probably from greater distances within Sundaland such as south Borneo and West Java. When these rivers carrying coarse rounded quartzose clastic material reached the coast, there was a rather narrow shelf and a steep slope, and much of this material would have been transported rapidly downslope into deep water, particularly during storms. There would be sandstones and conglomerates, debris flows and olistostromes, possibly including blocks of limestones eroded from the emergent carbonate islands. All these deposits would be very similar to those known from the Eocene to Miocene of West Java, such as the Ciemas Formation submarine fan and the Cikalong Formation olistostromes, and of Central Java, in the Karangsambung and Totogan Formations.

**Thrusting of the arc**

In West Java the flexural basin is almost completely missing (Figure 9), but its deposits are preserved, mainly in a narrow zone between the Jampang Formation of the Southern Mountains Arc and the shelf sequences north of the Cimandiri Valley. They are commonly steeply dipping but despite this, and evidence of locally deep water deposition, they are regarded as autochthonous deposits, and variations in interpreted water depths suggested to be due to contemporaneous vertical tectonic movements and changing eustatic sea level. We suggest that such interpretations are improbable. They require unlikely rapid vertical movements, invoke narrow elongate physiographic features unlike anything observed around Java at present, and ignore evidence of deformation. We suggest that all these features can be explained using the modern analogue for setting outlined above, with an elongate flexural basin formed north of the volcanic arc, which we term the Cimandiri Basin (Figure 9), that has subsequently been overthrust by the Southern Mountains Arc. This suggests total northward thrusting of the order of 50 to 100 kilometres.

In Central Java, the deposits of the flexural basin, which we term the Karangsambung Basin (Figure 9), are preserved in the Karangsambung and Totogan Formations, and overlain by the Miocene to Pliocene volcaniclastic turbidites that later filled the basin. These rocks are thrust northwards, but the overlying overthrust volcanic arc has been almost entirely removed by erosion on land. It is possible that in Central Java there was no equivalent of the Southern Mountains Arc of West and East Java and hence no significant overthrust arc. Volcanic arcs do often have significant gaps between volcanoes for uncertain reasons, and the load imposed by the volcanoes in West and East Java may have been sufficient to produce the flexural basin in Central Java. However, we suggest that it is more likely that in Central Java we are seeing a deeper structural level, as suggested by the more extensive exposures of pre-Cenozoic basement, and that the remnants of the arc are present offshore to the south.

In East Java, the deposits of the flexural basin are preserved in the Kendeng Basin (Figure 9). Although the basin had a similar form to that in West and Central Java, the basin fill is different. In West and Central Java most of the fill was sediments carried south from the Sunda Shelf, and the Cimandiri and Karangsambung Basins contain mainly quartzose material with subordinate volcanic
In East Java there was an extensive carbonate shelf to the north of the Kendeng Basin and relatively small amounts of continental clastic material was carried south into the basin, and that probably mainly during lowstands. Most of the fill therefore came from the volcanic arc to the south, which for much of the Oligocene and Early Miocene was emergent and explosive providing immense amounts of volcanic debris, particularly abundant volcanic quartz. Because of poor exposure of the Kendeng Basin sequences it is difficult to estimate the amount of thrusting along its southern edge. We estimate that there was only a few kilometres of thrusting of the Southern Mountains Arc in East Java.

**Age of thrusting**

The thrusting is Early Miocene or younger, but at present we cannot be certain of its exact age, nor if there was more than one episode of thrusting. This is largely due to the absence of critical dates at thrust contacts; in most cases it is possible only to determine that rocks older than Early Miocene have been thrust. An Early Miocene age could indicate that thrusting is linked to the termination of the Paleogene phase of arc activity on Java. There was regional plate reorganisation at this time following Australian continental collision in eastern Indonesia, which is suggested to have initiated counter-clockwise rotation of Borneo and Java (Hall, 1996, 2002), and contributed to cessation or diminution of arc volcanic activity (Macpherson and Hall, 1999, 2002) from Java eastwards in the Sunda Arc.

In the Cimandiri Valley field relationships indicate either Early Miocene or post-Middle Miocene thrusting (Figure 4). In northern Java van Bemmelen (1949) gives several examples of thrusting or associated deformation that is Late Miocene or Pliocene. Thrusting at this time could be associated with the shift of the location of arc activity to the north from the Southern Mountains to its present-day position (Hall and Smyth, 2007; Smyth et al., 2005). In East Java this is particularly clear since the modern arc volcanoes follow a simple linear trend, and the modern arc is parallel to and about 50 kilometres north of the Paleogene arc. In Central and West Java the arc also moved north by a similar distance but the modern volcanoes are distributed over a much wider zone than in East Java. The cause of the arc shift is not clear. Simandjuntak and Barber (1996) suggested a change from extension to contraction could be a consequence of subduction of the Roo Rise on the Indian Plate. There are certainly features south of Java that suggest collision of the Roo Rise is important (Figure 1); the forearc basins to the west and east disappear, the forearc is elevated, the trench shallows, and there is a change from subduction accretion to subduction erosion close to the trench (Kopp et al., 2006). However, it is not known when the Roo Rise arrived at the trench, nor why this would have caused the arc to shift north throughout Java.

**Structural division of Java**

We suggest Java can be separated structurally into three distinct parts which broadly correspond to the regions of West, Central and East Java (Figure 9). As explained above in West and East Java the overthrust volcanic arc is still preserved, whereas Central Java displays deeper structural levels below the volcanic arc which has been largely removed by erosion. However, the most important differences are between West-Central and East Java. The East Java Paleogene Southern Mountains volcanic arc was built on continental crust (Smyth, 2005; Smyth et al., 2005, 2007a, b). This had two important consequences; first, volcanoes were built from a base on land or close to sea level and hence were emergent at their earliest stages, and second, the volcanic activity was explosive Plinian-type for most of the Eocene to Early Miocene. The volcanic arc provided large quantities of debris in the form of volcanic ash to the Kendeng Basin from the Late Eocene until the Early Miocene. In contrast, the evidence from Cileteuh suggests that the volcanoes of West and Central Java were built on ophiolitic basement, the earliest volcanic activity was in a deep water setting, and the volcanic activity was basaltic and non-explosive. It was not until the Late Oligocene that the volcanoes had become emergent and were more explosive, as the crust thickened and the volcanic edifice became more substantial. Thus, the flexural character of the Kendeng Basin is more obvious because the basin formed on crust initially at sea level. In West and Central Java, the flexural contribution by volcanic loading to subsidence of the basin north of the arc would have increased with time, but the Karangsambung and Cimandiri Basins formed south of the shelf edge where there was already a slope and deepening to the south. Because of this morphology these basins were fed mainly by quartzose debris from Sundaland until the arc became sufficiently mature to be an important source of material.

We therefore consider the most fundamental structural division in Java is between Central and East Java (Figure 9), at the western limit of Archean
continental basement (Smyth et al., 2007b). Smyth (2005) interpreted a major NNE-SSW lineament at approximately 110.5°E (Figure 9) that we call the Muria-Progo lineament. This lineament links several major features onshore and offshore (Figure 1): a structural high in the Java forearc, the centres of three Oligo-Miocene volcanoes (van Bemmelen, 1949) in the West Progo Mountains, Mount Merapi and the unusual K-rich volcano of Mount Muria. To the east of this line the basement of the Southern Mountains is Archean continental crust whereas to the west it is Cretaceous ophiolitic rocks. Widiyantoro (2006) has observed a sharp boundary between low and high S-wave velocities in the depth range of 35-70 km below Central Java in his S-wave tomographic model. He suggested that this was the approximate edge of continental shelf during the Oligo-Miocene, based on Hamilton (1979). However, we do not agree that there was a sudden change in orientation of the shelf edge (Figure 9) and we suggest this seismic discontinuity is more likely to reflect the difference between old continental crust and younger thinner ophiolitic crust and their underlying mantle. The orientation of the lineament is quite similar to many cross-arc normal faults in East Java, and the normal fault that resulted in the 2006 Yogyakarta earthquake (Widiyantoro, 2006), suggests active arc-parallel extension at the present-day. Satyana (2006) suggested that a NE-SW fault in a similar position to the Muria-Progo lineament is one of a conjugate pair of strike-slip faults that bound Central Java. There is no surface evidence of strike-slip movement on either of the faults, but they have a similar orientation to the cross-arc normal faults in East Java, and could be extensional faults. Normal faulting on these faults would be consistent with the deeper structural levels exposed in Central Java and their position could be determined by changes in the character of the deeper crust as suggested above.

**Significance for hydrocarbon exploration**

The hypothesis of significant northward thrusting offers some new play concepts in southern Java. In East Java Eocene clastic sedimentary rocks containing coals would be more deeply buried near the thrust front, but the abundance of volcanic material in the Kendeng Basin could make reservoir rocks unattractive for exploration. However, in West Java the arc is thrust further northwards, the flexural basin sequence is likely to be shortened and stacked beneath the arc rocks and at the base of this thrust pile would be quartz-rich clastic rocks with abundant coals of Eocene and Oligocene age belonging to the southern Sunda Shelf. The seismic data from the offshore Malingping block suggest that the shelf margin sequences include a number of stratigraphic and structural traps, and these could be preserved below the thrusts. More subsurface information is required to test these suggestions.

**CONCLUSIONS**

After Cretaceous collision of an Australian microcontinental fragment with the Java-Meratus subduction system subduction ceased, and there was a passive margin south of Java until the Eocene. In the Middle Eocene subduction resumed, and a new arc developed south of the Sunda Shelf. The load of volcanoes contributed to the development of a flexural basin between the arc and the shelf that was between 50 and 100 kilometres wide, and followed the shelf edge running ENE the length of Java. From the Late Eocene to Early Miocene the basin was supplied with quartz-rich clastic sediments by rivers draining the Sunda Shelf in West and Central Java, with subordinate amounts of volcanic debris supplied from the arc volcanoes which were largely submarine and non-explosive. In East Java volcanoes were emergent earlier, and erupted explosively, and supplied greater amounts of volcanic debris to the basin to the north. Arc activity ceased for a period in the Early Miocene, and resumed again in the late Middle or Late Miocene at a location north of the site of the Paleogene arc. At some time between the Early Miocene and Pliocene the Paleogene sequence was thrust northwards, by more than 50 kilometres in West Java, but with probably much smaller displacements in East Java. Java can be separated into three structural sectors of West, Central and East Java. Central Java displays the deepest structural levels of thrusting and Cretaceous basement is exposed; the overthrust volcanic arc has been largely removed by erosion but may be present to the south of Java. In West and East Java the overthrust volcanic arc is still preserved. In West Java the arc is now thrust onto the shelf sequences that formed on the Sundaland continental margin. Northward thrusting of the Paleogene volcanic arc rocks of the Southern Mountains offers a simpler explanation than autochthonous models for stratigraphic and structural relationships in southern Java. Structural and stratigraphic traps beneath the overthrust arc may offer new hydrocarbon exploration possibilities.

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Figure 1 – Major features of the Java region between Borneo and Indian Ocean. Topography from SRTM and GTOPO30 and bathymetry from Sandwell and Smith (1997). Red boxes are numbered with the figures to which they refer in this paper. Red arrow shows the current Indian Ocean–Eurasia convergence vector at the Java Trench from McCaffrey (1996).
Figure 2 – West Java, Ciletuh region: SRTM image, key map and cross sections showing the structural interpretation discussed in this paper.
Figure 3 – West Java, Ciletuh region: (A) Interpretation of the Ciletuh Formation of Schiller et al. (1991) compared to (B) the new interpretation of the Ciemas and Ciletuh Formations discussed in this paper.
Figure 4 – West Java, Cimandiri Valley: Cross sections showing three possible interpretations of field relationships. A: Thrusting postdates the Middle Miocene; B: Thrusting is Early Miocene; C: Cimandiri Valley is strike-slip fault. Location of cross-section is shown on Figure 2.
Figure 5 – West Java, Rajamandala Limestone: Map and cross sections showing folding and thrusting of limestones north of Bandung.
Figure 6 – East Java, Prigi area: Tight folds in Middle Miocene limestones and volcanlastic sandstones.

Figure 7 – East Java, Wonosari and Batu Agung Escarpment: Map and schematic cross section across the Wonosari Limestone, Wonosari Trough deposits (Kepek and Sambipitu Formations) and underlying Lower Miocene volcanic rocks showing thrust interpretation. The Wonosari Limestone is interpreted to be thrust northwards, and the Kepek Formation is interpreted as the telescoped transition between the Wonosari Platform and the Wonosari Trough.
Figure 8 – Central Java, Karangsambung region: Geological map and cross section (simplified from Asikin et al., 1992) showing north-directed thrusting and folding of Eocene to Pliocene formations.
Figure 9 – Java: Summary tectonic maps showing (A) present-day interpreted structure and (B) schematic pre-thrusting relationships inferred between the Sunda Shelf, the Paleogene volcanic arc and sedimentary basins between them.
Figure 10 – East Java: Topography from SRTM and GTOPO30 and bathymetry from Sandwell and Smith (1997) to show modern analogue of the relationships between Sunda Shelf, the volcanic arc and sedimentary basins in the Paleogene, discussed in text. Surmised Pleistocene rivers are based on Voris (2000).