ABSTRACT

There are important hydrocarbon reserves in East Java in thick sedimentary sequences deposited to the north of the currently active and an older volcanic arc. The ‘East Java basins’ began to develop in the Eocene but they are not typical extensional or subduction-related basins. Subduction has been continuous to the south of Java since at least the early Tertiary, but surprisingly arc activity has not. A volcanic arc was active in southern Java from the Middle Eocene, much earlier than previously suggested, until the Early Miocene. There was a lull in the Middle Miocene and arc activity resumed and shifted about 50 km northwards in the late Miocene. There are significant volumes of quartz in Eocene and Miocene sands and conglomerates that are important hydrocarbon reservoirs. Previous studies have suggested that the quartz was derived primarily from Sundaland and/or from the basement. However, there were major palaeogeographical barriers between Sundaland sources and there is no significant quartz in basement rocks. New field observations suggest that most of the quartz has a volcanic origin and sequences described as primarily sedimentary contain much volcanic material. The volcanic contribution has previously been underestimated, partly because of the type of material. Volcanic products such as the ‘Old Andesites’ are easy to recognise but there are also large volumes of ash reworked in marine environments, which are the products of dacitic Plinian-type explosive eruptions. We suggest that most of the Eocene to Miocene sands and muds onland in East Java have a high volcanogenic content. Factors traditionally used to assess the maturity of sediment such as grain size distribution and grain morphology may not be applicable.

There are a variety of grain shapes, and sorting is a reflection not of maturity but volcanic processes. These new findings have important implications for provenance, reservoir properties and basin history in East Java.

INTRODUCTION

East Java is located on the SE margin of Sundaland (Figure 1A) and has been actively receiving sediment for much of the Tertiary. There is no evidence for old continental crust in East Java and most of what is presently land did not exist before early Tertiary times. This was, and still is, a very tectonically active zone. The products of a modern active volcanic arc and an early Tertiary volcanic arc are widespread and sedimentary basins are situated behind the ancient arc where there are thick sequences of Tertiary sediments and important accumulations of hydrocarbons. This paper is concerned with initial results from a study of onshore East Java. New data were obtained during recent fieldwork with the assistance of LEMIGAS, with further work continuing in the UK accompanied by dating studies in collaboration with CSIRO, Australia.

In East Java there are important deposits of quartz-rich sediments, which could be of exploration interest as potential reservoirs, and sources of sediment to offshore regions. The recent fieldwork showed the exposed basement lacks significant concentrations of quartz. Many of the sequences previously described as sedimentary are volcanic or reworked volcanic rocks, and volcanic material is present in almost every sequence of the basin. The volume of volcanic
material within the East Java sequences has previously been greatly underestimated although some units have been described as ‘tuffaceous’. Grains in some of the quartz sands have clear volcanic origins. The Jaten Sands of Pacitan contain abundant bipyramidal, faceted and embayed volcanic quartz grains. Quartz-rich crystal tuffs were found throughout SE Java. All these observations suggested that a re-assessment of the character and sources of quartz in East Java would be of considerable interest for exploration work, for interpreting the basin history, and for understanding the tectonic development of the region.

INTRODUCTION TO EAST JAVA

Present morphology

Any topographic map of Java shows the modern Sunda volcanic arc dominates relief of the island. The chain of volcanic mountains, which exceeds 3500m in elevation, occupies the central spine of Java. The other significant area of relief is the ancient volcanic arc in the Southern Mountains. Two other minor elevated regions in NE Java are the Rembang and Kendeng Hills. The new field studies indicate that the region behind the ancient Early Tertiary arc should be considered not as a single extending back-arc basin but rather as a series of basins. These basins may have different origins, provenance history and sediment fill. Two main basinal areas have been identified to the north of the ancient and modern arcs, which may be internally segmented. Based on these divisions and the original van Bemmelen zonation a modified, simpler zonation scheme has been developed.

Zones of East Java

This study divides East Java into four zones, based on stratigraphy and structure (Figure 1B), from south to north: the Southern Mountains, the present-day volcanic arc, the Kendeng and the Rembang Zones.

The Southern Mountains Zone contains the oldest surface exposures of sediments within East Java. Middle Eocene quartz-rich sands and conglomerates rest unconformably on Cretaceous basement and can be examined at Karangsambung, Jiwo and Nanggulan (Figure 1C). Material of volcanic origin has been identified even in these early basin sequences. The Oligocene is represented by andesites and dacites. These rocks, with various plutonic rocks, have previously been included in the ‘Old Andesites’ (van Bemmelen, 1949) but this term is not used here because it is not well defined and has previously been used in a variety of different ways. The axis of the Oligocene arc can be mapped from exposures and runs approximately east-west (Figure 1B). The axis of the Eocene arc is not exposed at surface today but is assumed to follow the same orientation as the Oligocene arc. Between volcanic centres are reworked pyroclastic deposits, which include sheet sands and turbidites.

North of the Southern Mountains products of the present-day volcanic arc cover the transition from the older arc into the Kendeng Zone. The Kendeng Zone is not well exposed and contains a thick sequence of Oligo-Miocene pyroclastic deposits that have been reworked in a submarine slope setting as sheets and fans associated with calcareous *Globigerina* pelagic muds. They resemble the reworked pyroclastic deposits found between volcanic centres in the Southern Mountains but have a more distal character.

The Kendeng Zone is very poorly exposed in the north and the passage into the Rembang Zone cannot be seen at the surface. The Rembang Zone contains a significantly different sequence to that seen within the Kendeng Zone, as shallow water carbonate and marine clastic deposits dominate, and there is little volcaniclastic material. Volcanic material is represented largely by thin ash deposits, which are present as clay bands. The Rembang Zone is the edge of the Sunda Shelf and sediments seen are typical of shelf-edge deposits. Seismic data suggest a horst block at the southern edge of the Rembang Zone, separating it from the Kendeng Zone, and this may be the cause of problems in correlating from north to south between the two depocentres.

The present-day structure of onshore East Java is illustrated by a cartoon cross-section (Figure 2) running N–S through the island from south of the Jiwo Hills to Mt Muriah, based on new field observations and some seismic data. Within the Southern Mountains Zone, strata proximal to the ancient arc dip gently toward the south coast. There are some local exceptions to this, such as at Karangsambung where high angle dips and thrusts can be seen. The Southern Mountains Zone has also been affected by late-stage extensional block faulting on NE–SW and NW–SE trends. To the north of the present arc the sequences within the Kendeng Zone
have been thrust northwards towards the Rembang Zone. In contrast, seismic sections through the Rembang Zone show no thrusting, shallow (<10°) southward-dipping reflectors, and open folding.

**Basement character**

The interior Sundaland core (Figure 1A) is continental crust which was assembled during the Triassic Indosinian orogeny and includes widespread granites of Triassic and Cretaceous age. The boundary between this continental core and a ‘transitional’ basement of East Java is usually traced through west Java towards the NE (e.g. Hamilton, 1979). The basement is thought to have a NE–SW structural grain and the current view is that arc and ophiolitic terranes were accreted to the edge of Sundaland during a subduction episode in the Late Cretaceous (e.g. Hamilton, 1979). The basement has influenced the sediment input to the basins by its structural grain which has affected basin geometry and current flow directions, and the basement has itself also supplied sediment by erosion from elevated intra-basinal high regions.

Of concern here is the composition of sediment from basement sources. There is no direct evidence for pre-Cretaceous continental crust in East Java, although some authors have shown a continental sliver in the East Java Sea based on Manur and Barraclough (1994). The most significant area of basement exposed within central and eastern Java is located at Karangsambung, Central Java where there is a large complex of ophiolitic rocks, the ‘Melange Complex’ of Hamilton (1979). Other rocks in the area are reported to be metamorphosed basic igneous rocks and metasediments associated with the ophiolites and arc rocks. In many places in Java depth to basement and the exact composition of basement are not known. On land in East Java the basement lacks significant quartz. The only exceptions are at Jiwo, where there are locally large quartz veins and some quartzose schists, and at Karangsambung where there are metacherts.

**Age and distribution of volcanism**

Volcanic activity in Java is poorly dated. There are only a few isotopic ages for volcanic rocks of Eastern Java and all of these ages were obtained through the use of whole rock K–Ar dating which has several inherent problems (McDougall and Harrison, 1998). Based on these few data Soeria-Atmadja et al., (1994) suggested that volcanism occurred in two phases in East Java. The first of these occurred between “40 Ma to 19-18 Ma” along an Early Tertiary arc in the Southern Mountains. They reported a lull in activity during the Middle Miocene. A resurgence, dated as “12-11 Ma” (Soeria-Atmadja et al., 1994) coincided with a shift of 50 km to the north in the position of the arc. It is not known why this shift occurred. Volcanic input can be identified in rocks from the Eocene. The volcanism was explosive, of Plinian-type, widespread and abundant. Plinian-type eruptions create large eruptive columns “which extend as high as 50 kilometres into the atmosphere” (Fisher et al., 1998). These eruptions are the product of “highly evolved rhyolitic to dacitic, trachytic and phonolitic magmas” (Fisher and Schmincke, 1984). These highly evolved magmas are intermediate to acid and therefore commonly rich in quartz. Plinian eruptions produce widely dispersed sheets of pumice and ash (Fisher and Schmincke, 1984) in the form of pyroclastic flows and ash-fall deposits. The volume of material is variable and depends upon the magnitude of the eruption and “volumes of Plinian fallout and pyroclastic flow deposits range from less than 1 to more than 3000 km³” (Fisher and Schmincke, 1984). Because of the height of the eruption column, the distribution of the deposits will be affected by the strength and direction of the wind and “ash may be carried around the world more than once from a single Plinian eruption” (Fisher et al., 1998).

Volcanic material has been identified in sediments dating from the Eocene but there are few Eocene rocks exposed in East Java and volcanic centres of this age cannot be identified. Extensive exposures within the Southern Mountains show the location of active volcanic centres in the Oligocene (Figure 1B). The arc is thought to have been located in the Southern Mountains from at least the Middle Eocene to the Middle Miocene. The ancient arc was a chain of volcanic islands that formed the southern edge of the marine basin system in East Java. The flanks of the volcanoes would have been vegetated and forested, with the lower slopes covered by mangrove swamps, forming deposits such as the Jaten Formation which contains silicified wood, and with river systems feeding into a shallow marine setting to the north (such as the Kebobutak Formation, Jiwo). Reefs were locally developed (Campurdrarat Formation) between dormant volcanic centres or within calderas that provided shallow water.
environments. Fringing reefs like those seen around Bali may also have formed. Within the deeper water parts of the forearc and immediate backarc region there were fans of volcanogenic turbidites, similar to those identified in the Jiwo Hills. Further out towards the Java trench pelagic sediments would have dominated.

POTENTIAL SOURCES OF QUARTZ

There are several potential sources for quartz in the East Java sequences. Each is discussed below in terms of location and in the context of palaeogeographic maps (Figure 3) of Sundaland and its SE margin.

Metamorphic and vein quartz

Metamorphic and vein quartz may be directly eroded from the Cretaceous basement. The basement lithologies at Karangsambung and Jiwo include phyllite, chert, greywacke, basalt, granodiorite and schist. As discussed above, large quartz veins are present at Jiwo and Karangsambung. However, these rocks could not be sufficiently large sources to supply the volumes of Lower Tertiary quartz sands. Further to the north are the Karimunjawa and Bawean Arches which are thought to have been emergent during the Paleogene but are now submerged beneath the East Java Sea. These could be potential sources for metamorphic quartz but information is scarce from these areas. Rocks from this region are reported to include diorite (Ben-Avraham and Emery 1973) and pre-Tertiary recrystallised slates, quartzites and quartz conglomerates (van Bemmelen, 1949). A further source but even further away is the Sundaland itself. Extensive Triassic and Cretaceous granites are well exposed in the Malay Peninsula and SW Kalimantan and are associated with metamorphic rocks.

Recycled sedimentary quartz

Detrital quartz may be derived from Cretaceous basement rocks and, in places, Cretaceous sediments described as resting unconformably on even older basement rocks. Recycled sedimentary quartz may be derived from the basement sequences where cherts and greywackes have been identified. However, none of the basement sediments are coarse-grained enough to provide sands characteristic of the Nanggulan Formation and other Eocene formations. Mathews and Bransden (1995) reported over 3 km of Cretaceous sediments from offshore East Java within truncated synclines. Recycling of sediments like these could have provided quartz to the basin at early stages in the basin history but the composition of these sediments is unknown. They are overlain offshore by Eocene sediments. Most sediment derived from still further north in Sundaland would probably have been trapped in the sedimentary basins of the Sunda Shelf. However, any sediment eroded from this region would need to have by-passed several large emergent ridges in the Java Sea, and intervening basins, which would have acted as sediment traps.

Plutonic rocks

The granitic bodies closest to the East Java region are concentrated some distance into the very core of Sundaland. The bodies include the Schwaner Mountains, the granites of the Tin Belt in the Malay peninsula and the tin islands of Sunda shelf: Bangka, Billiton and Belitung. Again the major highs and potential traps within the East Java Sea would have prevented sediment entering East Java (Figure 3). There is some evidence for Gondwana continental crust beneath south Sulawesi from mapping (Wakita et al., 1996) and geochemistry (Bergman et al., 1996) although it seems improbable that these rocks were available for erosion from the Eocene onwards in a region actively extending and subsiding, which was also very distant from East Java. Finally, there is also a slight possibility that a fragment of continental crust may have been present to the south of the Southern Mountains arc, perhaps accreted during subduction at the Java Trench. This would have important implications for reconstructions (Figure 3) and the geochemical evolution of the arc but it is difficult to see how sediment could bypass the accretionary wedge, forearc and the arc to enter East Java. This is the least likely source of quartz.

Volcanic quartz

There are several mechanisms whereby crystals can be concentrated from a volcanic source. Well-sorted single crystals, angular shards or fragments can be produced by single eruptions due to concentration within the magma chamber, in the eruption column, or by reworking and weathering of tuffs, ashfalls and pyroclastic debris in a tropical environment (Cas and Wright, 1987). The new fieldwork shows that the volcanic rocks in East Java include abundant dacites as well as the well-known andesites. Dacites are
typically highly viscous, may be quartz-rich, and commonly form domes (as observed in the field) which are often associated with explosive Plinian-style eruptions producing ashfall and flow deposits. The size of the area covered by any ashfall or flow deposit will be of importance for this as a potential source. Elsewhere in the Sunda Arc, during the Pleistocene, the Mt Toba eruption, which occurred at 75,000 BP, was a catastrophic event of the type that would typically reoccur on a timescale of 100,000 to 1,000,000 yr (Fisher and Schmincke, 1984). The calculated volumes of “as much as 2000 km³ of ash flow and 2000 km³ of ashfall were erupted” with ash flows travelling some “100 km” from the volcano (Knight et al., 1986). The ash produced was deposited over the entire SE Asian region. Thus, during the period of about 20 million years of the Eocene-early Miocene volcanic activity there could have been numerous eruptions on the scale of Toba, and many more of smaller scale. In the Early Tertiary the volcanic deposits either flowed directly into the sea or were reworked in littoral to offshore environments. The active arc was clearly capable of providing high concentrations of quartz as pulsed and background input into the basin for at least 20 Ma. On a lesser scale Mt Merapi, Central Java, has frequently produced large pyroclastic flows and lahars and is especially susceptible to dome collapses (Boudon et al., 1993). These pyroclastic deposits have since been reworked to volcanic soils.

CHARACTERISTICS OF QUARTZ FROM DIFFERENT SOURCES

Different quartz types can be recognised by a number of criteria used individually or combined. These can be used to distinguish quartz grains from different source regions, and can be used in combination with the characteristics of other grains or minerals to identify provenance.

Metamorphic and vein quartz

Quartz of a metamorphic origin has several diagnostic characteristics which allow the grains to be distinguished from other sources. Metamorphic quartz can have a monocry staline or polycrystalline character. When the metamorphic grains are monocry staline, undulosity can be observed in thin section. As extinction is not straight in these crystals but sweeps across the grain, the angles over which extinction occurs can be measured, even in the absence of a distinctive crystal edge. This measurement is the undulosity extinction angle, this angle is generally greater than 5° (Leeder, 1982). Polycrystalline grains are common in metamorphic quartz and relatively few occur in igneous rocks: “the amount of polycrystalline quartz is least in plutonic quartz; it increases in high-grade metamorphic rocks and is highest for low-grade metamorphic rocks” (Leeder, 1982). The number of crystal units found within the polycrystalline quartz “is greatest in low-grade metamorphic rocks and least in high-grade and plutonic igneous rocks” (Leeder, 1982). This illustrates a method by which metamorphic and plutonic quartz may be distinguished. Vein quartz is commonly “milky white colour imparted by fluid inclusions” (Tucker, 1987).

Recycled sedimentary quartz

Chert is easily recognised in thin section, and like that from greywackes and silts, is fine grained or microcrystalline. Detrital quartz that has been through multiple cycles of erosion will have several distinctive characteristics. The grains are commonly rounded, pitted and may have corrosion rims. These grains often exhibit abundant fluid inclusion trails as “most sedimentary diagenesis involves at least some recrystallisation, overgrowth, or new growth phase. These new crystals trap fluid as inclusions” (Roedder, 1984). These trails of inclusions are very different from the melt inclusions identified within volcanic quartz. The inclusions are typically very small and form strings throughout the grain often following fracture patterns. Melt inclusion are formed at the time of mineral growth and often much larger with a shape resembling the crystal grain boundaries. Grains may also be etched and overgrown. Because of diagenetic overprints it is often impossible to determine the original source of the quartz.

Plutonic quartz

Igneous quartz as described above generally contains few polycrystalline grains. Where the grains are polycrystalline the “crystal unit” will be <3 units. The undulose extinction angle of this form of quartz is typically <5° (Leeder, 1982). Other features that are seen within igneous quartz include healed fractures, milky white colour to translucent, crystals may be zoned, “quartz typically forms anhedral grain but it may show euhedral outlines in fine grained rapidly cooled” rocks, “in some rocks quartz may later suffer
magmatic corrosion” (Deer, Howie and Zussman, 1998).

**Volcanic quartz**

Volcanic quartz can be very distinctive when fresh. When quartz cools very rapidly, it may have a clear non-undulose form and “almost all quartz of volcanic origin is of the single crystal type” (Leeder, 1982). Crystals in volcanic deposits are commonly bipyramidal and can commonly have a negative crystal forms, or be present as skeletal crystals, that form due to the reaction with melt in a high-level magma chamber. Embayments are common and are distinguished from etching caused by corrosive formation waters by their shape. Rounded embayments (Donaldson and Henderson, 1988) formed by a “gas bubble in the melt approaching the crystal” and a subsequent reaction with the melt. Other volcanic features include well-developed zonation, melt inclusions, microcrystalline or fibrous quartzo-feldspathic growth concentrated on a crystalline core, cracked tile-like fracture patterns and healed fractures. After a period of erosion it may be very difficult to identify all these features, as fractures would be promoted on these points of weakness, but some are usually present.

**Other provenance indicators**

In sediment of a first-order cycle, lithic fragments representing the underlying basement lithologies would be common. Clay minerals can also give some indication of provenance. Serpentine (antigorite, lizardite, chrysotile, amesite, berthierine, and greenalite) is formed by retrograde metamorphism caused by a low temperature hydrothermal alteration. This type of reaction is common in ophiolitic ultrabasic rocks that are found within the basement. Illite may also be found since its “principal occurrences are by diagenetic/low grade metamorphic processes” (Deer, Howie and Zussman, 1998). Chlorite (clinochlore, chamosite, pennentite) is also diagnostic of the erosion of low to medium grade metamorphic rocks (Deer, Howie and Zussman, 1998). Some minerals that would be expected in association with plutonic quartz would be various feldspars, micas would be abundant and there may be other accessory minerals. Illite and chlorite would be expected. Other minerals and grains found in association with volcanic quartz include plagioclase feldspar, hornblende, pyroxene, zeolites and devitrified glass shards. Many of these grains may share the characteristics of volcanic quartz, such as zonation, embayments and melt inclusions. Smectite and some kaolinite clays are commonly present in volcanic deposits.

**PROVENANCE OF QUARTZ-RICH EAST JAVA SANDS**

Figure 4 shows the locations of the quartz-rich sections studied in East Java. The quartz-rich sands of Eocene age can be examined at Karangsambung, Nanggulan and Jiwo (1, 2 and 3 on Figure 4) and the Miocene sands at Pacitan, Lutut and Ngrayong (4, 5 and 6). General petrological analyses have been carried out on these sands. Point counts (300 grains/slide) were used to categorise the sands. This enabled any variations of other rock-forming grains, like feldspars and volcanic lithic fragments, or the abundance of metamorphic lithic grains to be determined. Dickinson plots are the standard method used to identify source regions, but many of the sands examined in here are not QFL (Quartz, Feldspar and Lithics) sands and plotting does not enable trends to be distinguished. Alternative triangular plots, based on the Dickinson plots have been developed adopted, the new plots highlight trends as with the QFBl (Quartz, Feldspar and Basement lithics) in Figure 5. Detailed quartz provenance studies have also been carried out. Criteria were established to allow the identification of quartz types. Specific quartz-type point counts were made to determine the compositional variation of the East Java sands. A minimum of 100 grains were counted for each slide. Several problems exist with overprinting due to burial, prolonged transportation and recycling. Grains with uncertain categories have been assigned to a general or unknown field. Details of each of these counts are shown in Figure 4.

**Oldest sediments within the basin**

Samples taken from a conglomerate immediately above the basement at Karangsambung have a pure metamorphic basement source. This can be seen in the triangular diagrams (Figure 5). This conglomerate can be examined along Kali Lokulo and has been assigned to the Lokulo Member of the Karangsambung Formation (Figure 6). Further up-section at Karangsambung it is evident that a transition occurs and the deposits become enriched by volcanic material. The pure basement-derived units
can also be seen in isolated channelised conglomeratic sands at Nanggulan (middle Eocene) and in localised exposures in the Jiwo Hills. The age of these sediments is uncertain. The rounded character and the size of the clasts (Figure 6) suggest that there could have been several cycles of erosion and redeposition before final deposition.

**Eocene quartz-rich sands of Central Java**

Thick sand sequences have been identified at Nanggulan and also at Karangsambung. These are well-bedded units above the lithic-rich Conglomerates. They are arkosic arenites and quartz arenites with variable compositions. Nummulitic limestone beds are frequent. A rapid transition above the conglomerates has been identified in the Karangsambung region as can be seen from the point count analysis (Figure 5). Lithic grains of basement lithologies become less abundant up-section and fresh feldspars increase. Within these sequences volcanic quartz becomes increasingly dominant up-section.

**Miocene quartz-rich sands of SE Java**

The Jaten Formation can be examined to the NE and NW of Pacitan. Within this formation the facies vary rapidly up-section and laterally from terrestrial to shoreline to shallow marine. The sands of the Jaten Formation contain many distinctive features indicating they have a volcanic origin. The grains were studied in detail to identify the principal characteristics of volcanic quartz, to help recognise volcanic quartz within other sequences that have a less obvious origin. In several locations there are significant concentrations of bipyramidal quartz grains up to 10 mm across. Under the microscope and SEM (Scanning Electron Microscope) these alpha quartz (confirmed by X-ray diffraction (XRD) study) crystals have abundant features indicating a volcanic origin. The grains either have perfect crystal faces or alternatively have large embayments with features indicating crystal-melt interaction producing multiple phases of crystal growth (Donaldson and Henderson, 1988). Other features identified include skeletal grains, negative crystals, cracked tile-like fractures, zonation, tracks or scours along the crystal surfaces and microcrystalline surface growth. Photomicrographs and SEM images illustrating these features are shown in Figure 7.

**Miocene quartz-rich sands of NE Java**

*a. Ngrayong Sand*

The Ngrayong Sand is well exposed in quarries along the Lodan Anticline. The sand has been described as a mature clean quartz sandstone. From outcrop data alone this is a valid description, based on the ‘clean’ aspect, white colour and friable nature. However, thin section examination shows that many of the quartz grains are very angular, not what would be expected from ‘mature’ sand recycled and transported over great distances. There are embayments indicative of volcanic sources as well as melt inclusions in several grains. Much of the quartz is non-undulose and exhibits no other features. Zircons are also present within this unit. The sands contain thin mud units that appear to be ashfall tuffs reworked into a marine environment. Examinations of these muds by XRD show significant proportions of montmorillonite, a smectite that is suggestive of a volcanic setting. These samples also contain illite and chlorite indicating background erosion and reworking of a metamorphic basement.

*b. Lutut Sands*

The Lutut Beds occur in Kali Lutut, Semarang and are often hidden below raised water levels in times of flood. They have been omitted from many recent geological maps and their reported age is Early Miocene (personal communication, P.Lunt, 2000). The sands contain quartz, basement fragments, lithic fragments, volcanic fragments and large pieces of vitreous carbon. Interbedded with the sands are finer muddy sequences. The unit is composed of many fining-upward channelised sequences. These are laterally extensive but vary in thickness. Many of the beds are sheet-like. There are no sedimentary structures present which identify the environment of deposition and the beds are not bioturbated. All of the lithic clasts within these sands appear to be basement-derived, and reworked with clasts frequently showing rounding on one side and sharp broken surfaces on others. Much of the quartz from the Lutut Sands is polycrystalline or undulose, suggestive of a metamorphic recycled basement source. The sands also contain tosudite, a smectite mineral that “commonly forms as an alteration product of volcanic rock” (Deer, Howie and Zussman, 1998).
Other features of the quartz-rich sands

a. Mica content

Another feature of the sediments that supports a non-continental source is the lack of mica. From over 50 point counts at all levels within the sedimentary sequence only one grain of muscovite mica was identified. Sediments from a granitic source would yield significant volumes of mica whereas the basement lithologies described from Central Java, or local volcanic rocks such as andesites or dacites, lack this mineral.

b. Sediment sorting and maturity indices

Sediments from an air-fall deposit generally contain well-sorted material, which can create problems when assigning a maturity value to the sediment. Traditionally composition and angularity are used. Concentrations of mineral phases can take place within the magma chamber and sorting can occur within the eruption column. So a relatively fresh volcaniclastic sequence may appear texturally mature in terms of grain sorting but not in terms of roundness. This highlights the importance of detailed examination of the sequences.

Unusual features of the Eocene sequences

At Karangsambung, the Jatibungkus Limestone is surrounded by volcaniclastic sands (Lunt et al., 1998). This limestone is an isolated block and forms several mound-like hills to the south of Desa Karangsambung. The shallow marine limestone is reported to be of Late Eocene age (Paltrinieri et al., 1976) as are the surrounding volcaniclastic sands. This isolated block has been interpreted as a block (olistolith) within an olistostrome. An olistostrome is a mass flow deposit, typically consisting of a chaotic mass of intimately mixed blocks and muds which forms by submarine gravity sliding or slumping. A slope is required and they typically form in deep marine settings. In the Jiwo Hills at Gunung Pendul, another unusual Eocene sedimentary unit can be seen. This is a rock which contains abundant large Nummulites in a mud matrix with includes large angular fragments of metamorphic basement rocks. The Nummulites, a benthonic foraminifera, occur as single tests with no apparent reworking and as part of lithic clasts. The mud matrix would suggest a relatively open marine environment but the occurrence of the non-reworked benthonic foraminifera is difficult to explain. An alternative emplacement mechanism is by volcanic processes. As the Jatibungkus Limestone is a block effectively floating within sheet-like volcanic sands, it is plausible that a volcanic eruption creating a powerful pyroclastic flow or lahar, could pick up and carry blocks from a shallow marine environment. A volcanic eruption and related pyroclastic flows or lahars could also account for the Pendul Nummulites beds. Such flows could remove material from a shallow marine setting and redeposit it, en masse, further offshore. This would explain the non-reworked nature of the foraminifera tests and the odd association of muds, metamorphic clasts and fossils. Probable volcanic ash layers are seen in the sequence at Pendul a few meters above the little above the Nummulitic mudstones. Further work on the clays is required to test this hypothesis.

NEW AGES FOR IGNEOUS ACTIVITY

A number of radiometric dating methods are being applied to extrusive and intrusive igneous rock samples from East Java. Methods being used include (Uranium-Thorium)/Helium and fission track dating of apatites and Potassium-Argon (K-Ar) and 40Ar/39Ar dating of potassium-bearing minerals. The longer-term objective in obtaining these data is to place the igneous evolution of Java and associated regional uplift and cooling histories in a precise temporal framework. In this contribution we report the initial results obtained using K-Ar whole rock dating and Uranium-Lead (U-Pb) dating of zircons by Sensitive High Resolution Ion Microprobe (SHRIMP).

The K–Ar method is based on the accumulation of 40Ar (radiogenic argon) produced by the radioactive decay of 40K (McDougall and Harrison, 1998). As with any radiometric dating it is a prerequisite that the system being analysed has behaved as a closed system. Thus the K-Ar whole dating of an igneous rock can only yield a valid crystallisation age if there have been no losses or gains of parent 40K and/or radiogenic argon from the primary potassium-bearing minerals. All the rocks at surface in East Java are affected by some degree of tropical weathering. Scanning electron microscope observations of the primary potassium minerals, K feldspar and hornblende, reveal the effects of such weathering in dissolution features and secondary alteration products
including illite, a potassium-bearing clay mineral. Dissolution processes will result in losses of parent and daughter isotopes. The formation of illite will introduce a new potassium-bearing mineral possibly formed over a significant span of time and possibly of significantly younger average age. Thus whole rock samples will not comply with the requirement of a closed system with respect to K-Ar dates because of the alteration experienced by the minerals.

An illustration of this problem is evident in dated samples from the Kerek Formation in which two beds literally meters apart have an apparent 35 Ma age difference. The section in outcrop is a continuous sequence of volcaniclastic sandstones. The samples are practically identical in hand specimen and thin section. The sample lowest in the sequence gave an age of 50.7±1.27 Ma and the sample just meters above was dated as 16.65±1.11 Ma. Another tuff from the Kebobutak Formation in the Baturagung escarpment (south of the Jiwo Hills) was dated using the whole rock K–Ar method as 6.51±0.86 Ma and as 29.2±1.4 Ma by the ion probe U–Pb method on zircon. The Late Oligocene zircon age is consistent with the other area, including biostratigraphic data and its position within the basin sequence. Ar–Ar dating of samples is in progress.

SHRIMP U–Pb isotopic data (Table 1) have yielded a precise Oligocene eruptive age from zircons separated from a Kebobutak Formation tuff from Jiwo at 29.3±1.4 Ma. In contrast, zircons from two tuffaceous sediments have yielded rather scattered data. For a Sambipitu Formation sample from Wonosari this is as a result of two distinct age populations defining precise ages at 12.8±0.2 (8 grains) and 18.6±0.2 Ma (6 grains). It would seem that two distinct eruptive events have been sampled by zircons in these sediments, possibly involving reworking of material from the older event. For a Semilir Formation sample from Jiwo individual dates for 17 grains range from 19Ma to 31 Ma, defining a mean age of 25.9±0.8 Ma. This does not define a single eruptive event but rather a variable sedimentary sampling of zircons crystallised at different times over a period of ~12 Ma of igneous activity in the same region.

SHRIMP U–Pb zircon dates indicative of intrusion ages were obtained for three samples. The ages range from Late Oligocene at ~25 Ma (1 grain, two spot analyses) for a diorite from Nanggulan, to Late Miocene at 9.3±0.2 Ma (20 grains) for a diorite from Ponorogo, and at 5.7±0.5 Ma (22 grains) for a diorite body at Trenggelek (Table 1). However, the Late Oligocene diorite from Nanggulan, a granodiorite from Jember, and volcanic breccia clasts from Turen also yielded ranges of very old zircon ages. For these three samples 16 of a total of 41 zircon ages were between 500 and 600 Ma. The remaining 25 ages are > 600 Ma and range up to 3200 Ma (Figure 8). This has implications for the source of the melt beneath the volcanic arc. There are three possible sources for these old zircons. They were derived from continental sediment on the down-going plate subducting beneath Java during the Paleogene, from continental crust included in the basement beneath the Paleogene arc, or from a continental fragment was subducted beneath Java. In all cases, the zircon ages imply an old continental source such as crust now found for example in Western Australia, Eastern Antarctica and Southern India. If the zircons were derived from subducted sediment originating from Australia or Antarctica this would imply transport of the sediment far to the north onto the Indian plate during the Paleogene. If a fragment of crust was subducted below or accreted to Java it would imply the existence of a microcontinental fragment which originated from Gondwana, and was separated by Mesozoic rifting of the Gondwana margin. Magma rising from the subduction zone could intrude this continental sliver if accreted to Java and assimilate the zircons prior to eruption. Alternatively, if the subducting slab included a microcontinental fragment, its partial melting could release old zircons into the rising magma. Tectonic reconstructions (Hall, 2002) show that these are not implausible possibilities. Further work is required to test such ideas.

RELEVANCE OF THIS STUDY TO PETROLEUM SYSTEMS

The integrated application of field observations and geochronological and petrographic methods has generated data critical to reconstruction of the thermo-tectonic history of the East Java basinal system. This has direct impact on quantifying the process elements of a petroleum system such as source rock maturation, sedimentation, burial, structuration and oil and gas formation. Specifically, the relevance of the study to petroleum systems analysis lies in:

1) Volcanic material has been identified in almost all sediments dating from the Eocene to the
present day. Many of the sequences previously described as sedimentary are volcanic or reworked volcanic rocks, and volcanic material is present in almost every sequence of the basin. The volume of volcanic material within the East Java sequences has previously been greatly underestimated. Volcanogenic contributions to the sediments have important implications for provenance, reservoir properties and basin history in East Java. The demonstration of a volcanic origin for many of the quartz sandstones indicates that careful consideration is required before conventional indicators are used to interpret maturity. The widespread presence of volcanic clays means that the value of these sands as reservoirs may be considerably reduced.

2) The volcanic arc activity started much earlier than previously thought. This is significant in understanding the influences on basin development (heatflow, creation of new sedimentary sources and supply directions, burial and uplift, creation / destruction of carbonate reef environments, stress fields, fluid flow events, reservoir diagenesis).

3) Volcanogenic zircon U-Pb ages from the Eocene–Miocene sedimentary succession allow precise dating of some of these volcanic events.

4) The occurrence of 500 to 3200 Ma zircon ages from intrusive rocks has significant implications for the source of the parental melts. The zircon age distributions may imply melt contributions from a continental fragment that had been included in the basement or has been subducted beneath Java. Such a fragment would most likely have originated from Gondwana and was separated by Mesozoic rifting of the Gondwana margin. A continental fragment as basement and geographically associated with an arc may have had significant effect on stress regimes in both the near and far field.

5) Some important characterization of ‘Old Andesite’ Eocene–Miocene arc-related rocks in time and space has been achieved. Continued work will be used to assess the importance of the arc activity and its effects on petroleum systems development. In particular, this will aid assessment of uplift events creating new provenance areas, and hydrothermal effects on diagenetic pathways, promoting petroleum generation, migration and remigration. The improved tectono-stratigraphic framework will aid correlations of wells and seismic profiles.

6) Zircon U-Pb crystallization ages from intrusive rocks, when coupled with other mineral geochronometrical methods such as fission track, (U-Th)/He, \(^{40}\)Ar/\(^{39}\)Ar, K-Ar and Rb-Sr can be used to interpret uplift and cooling rates. This will result in improved understanding of the timing of major uplift in the region, and of sediment supply rates and provenance.

CONCLUSIONS

Quartz with a volcanic origin forms a significant proportion of the quartz-rich sands of East Java. The quartz is distinctive and many characteristics indicating a volcanic source have been recorded. The Eocene quartz-rich sands have a mixed provenance of metamorphic, recycled sedimentary and volumetrically important volcanic material. All the Eocene to Lower Miocene sediments of East Java appear to lack material from a plutonic source whereas material of volcanic origin has been identified in almost every part of the sequence. There is no sign of material derived from Sundaland or any other continental crust. The influence and extent of volcanism has been greatly underestimated in East Java, partly because of the type of material. The ‘Old Andesites’ are easy to recognise but there are large volumes of ash reworked in all sequences, which are the products of dacitic Plinian-type explosive eruptions. Factors traditionally used to assess the maturity of sediment such as grain size distribution and grain morphology may not be applicable to quartz-rich sands from volcanic sources such as these. Volcanic ash is often extremely well sorted as a result of the eruptive processes and sorting is not a reflection of maturity. Up to now the age database for East Java has been limited to a few whole rock ages based on the K–Ar method, which has problems with the altered or weathered lithologies typical of Java. New work undertaken using the SHRIMP method on single zircon crystals is producing promising results and new information. The intrusions of SE Java contain zircons with ages recording emplacement and also zircons of much greater age, providing insights into the origin of the magma involved in the Early Tertiary arc volcanism, and the nature of the crust beneath Java. Further work will enable the accurate
dating of volcanic activity in East Java. The abundance of volcanic material in Eocene to Lower Miocene rocks needs to be considered when planning exploration in East Java on land, and also suggests an important potential source of quartz for sands deposited to the north in the offshore basins.

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REFERENCES


**TABLE 1**

**SUMMARY OF ZIRCON U-PB SHRIMP DATA**

<table>
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<th>Sample No.</th>
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<th>Error +/- 2 sigma</th>
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**TABLE 2**

**HISTOGRAMS OF ZIRCON AGES FROM 3 INTRUSIVES, EACH SHOWING SIMILAR AGE PROFILE WITH A PEAK CORRESPONDING TO PAN AFRICAN TIME AND TAILING TO MESOPROTEROZOIC AND OLDER AGES. SUCH PROFILES MIGHT BE EXPECTED FROM A SLIVER OF RIFTED GONDWANAN CONTINENT SUCH AS FROM WESTERN AUSTRALIA, EASTERN ANTARCTICA OR SOUTHERN INDIA.**
Figure 1 - A) Regional plate tectonic setting of SE Asia. The area of East Java discussed here is highlighted by a red box. B) New simplified zonation scheme for East Java. C) Fieldwork locations highlighted with red stars.
Figure 2 - Cartoon regional cross-section drawn from the Jiwo Hills in the south to Mt Muriah in the north based on new field observations and seismic data. The summary of stratigraphy is based on new field observations and information from de Genevraye and Samuel (1972); Kadar (1986); Ardhana (1993); and P. Lunt, pers. comm. (2002).
Figure 3 - Early Tertiary palaeogeography showing potential sources for quartz-rich sediments.
Figure 4 - Results of point counting of quartz grains showing different sources. 1: Lokulo Member of the Karangsambung Formation (1a is taken from the base of the section where quartz from a metamorphic basement dominates, and 1b is higher in section). 2: Kali Songo Member of the Nanggulan Formation (2a is at the base of the sequence and 2b about 100m up section). 3: Cakaran Member of the Wungkal Gamping Formation in the Jiwo Hills (3a is lower in section and 3b is a sequence towards the top of the formation). 4: Jaten Formation, Pacitan. 5: Lutut Sands, Semarang. 6: Ngrayong Sands, Rembang.

Figure 5 - Triangular diagrams of sandstone detrital modes showing changes in composition up section in Eocene sequences.
Figure 6 - Images of the Eocene quartz-rich units. A) Basement derived polymict conglomerate from the Lokulo Member of the Karangsambung Formation. Note large vein quartz clasts. B) Channelised conglomeratic sandstone of basement origin from the Kali Songo Member of the Nanggulan Formation, Central Java. C) Photomicrograph of the Lokulo Member of the Karangsambung Formation. Microcrystalline chert and polycrystalline quartz are in abundance. Note clear angular volcanic quartz. D) Photomicrograph of metamorphic quartz from the Cakaran Member of the Wungkal Gamping Formation, Jiwo Hills. White bar = 1mm in photomicrographs.
Figure 7 - Images of volcanic quartz-rich sands of the Jaten Formation, Pacitan. A) Concentrations of bipyramidal quartz grains at outcrop scale, Desa Jaten. B) Bipyramidal crystal. C) Photomicrograph of rounded embayments. D) Photomicrograph of ocelli texture. E) SEM image of rounded embayments and melt reaction textures. F) SEM image of microcrystalline growth on the surface of the grain. White bar = 1mm in photomicrographs.