ABSTRACT

The Seram Trough is located in the northern part of the Banda Arc–Australian collision zone in eastern Indonesia and is currently the site of contraction between the Bird’s Head and Seram. It has been interpreted as a subduction trench, an intracontinental thrust zone and foredeep, and a zone of strike-slip faulting. Recently acquired 2D seismic lines help interpret its tectonic evolution. Folding in the Early Pliocene formed an anticlinorium between Misool and the Onin Peninsula of Irian Jaya. A newly recognised Pliocene angular unconformity truncates sediments as old as Middle Jurassic and is an ancient topographic surface with significant relief. It was later folded and now dips south towards the trough where it is covered by up to 3 km of sediments. Initial tilting of the unconformity surface was accompanied by deposition of a transgressive sequence which can be traced into the trough. This is overlain by two sequences which prograde towards the trough. These show progressive rotation of the unconformity surface, gravitational displacement of sediments into the trough, and thrusting which continues to the present day. Contraction occurred in the trough from the Early Pliocene and is younger than the previously suggested Late Miocene age. Thrust faults in the trough deform sediments deposited above the unconformity and detach at the unconformity surface. On Seram thrust faults repeat Mesozoic–Miocene sequences and probably detach at their contact with metamorphic basement. The detachment surface must cut through the Mesozoic–Miocene sequence between Seram and the trough. This work suggests the Seram Trough is not a subduction trench but a foredeep produced in response to loading by the developing fold and thrust belt of Seram, with an associated peripheral bulge to the north.

INTRODUCTION

The Seram Trough is located between the islands of Seram and Misool in eastern Indonesia (Figure 1). Eastern Indonesia is a complex region located in the zone of convergence between the Eurasian, Indo-Australian and Pacific plates. The major geological feature is the Banda Arc which consists of an inner volcanic arc and an outer non-volcanic arc of islands formed of sedimentary, metamorphic and some igneous rocks mainly of Permian to Quaternary age. The inner volcanic arc has been active since the Late Miocene (Abbott and Chamalaun, 1981; Barberi et al., 1987; Honthaas et al., 1998). The outer arc is widely regarded as a recent zone of collision between the Australian continental margin and the Banda volcanic arc and includes thrust sheets, principally of Australian sedimentary rocks but associated in places with some igneous and metamorphic rocks, which have been elevated above sea level very rapidly since the mid Pliocene. On the external side of the outer arc is a deep trough which runs for almost 2000 km from the Java Trench via the Timor Trough to join the Seram Trough, curving in a U-shape to enclose the deep Banda Sea. The significance of the trough is still debated. Some authors (e.g. Hamilton, 1979; Karig et al., 1987) interpret it as a subduction zone separating the Australian and Eurasian plates whereas others (e.g. Audley-Charles, 1986; Tandon et al., 2000) suggest it is a foredeep at the front of a developing fold belt. It has also been suggested that the Seram Trough might be a zone of strike-slip faulting (e.g. Linthout et al., 1997; Milsom et al., 1983) but it is now generally agreed to be the site of southward underthrusting of the Bird’s Head (northwest New Guinea) beneath Seram. However, debate continues.
about whether it is a zone of intra-plate shortening or a subduction trench, and among those who argue for subduction there is disagreement over whether there is a single slab which curves around the arc (Hamilton, 1979; Milsom, 2001) or two separate slabs dipping in opposite directions (Bowin et al., 1980; Cardwell and Isacks, 1978; McCaffrey, 1989).

2D seismic surveys shot along the Seram Trough (Figure 1) by TGS-NOPEC Geophysical Company in 1998 and 1999 were studied in order to better understand the tectonic evolution of the area. The aims were to focus on the relationship between stratigraphy and structural styles, particularly for the Neogene to Quaternary, to investigate whether the Seram Trough is a subduction trench or a zone of intra-continental shortening, and to identify the sequence of events which led to its development.

STRATIGRAPHY OF THE REGION

The Seram Trough separates the islands of Seram and Misool, which is linked geologically to the Bird’s Head. The horizons interpreted on the seismic lines were tied to wells north of the trough, in offshore parts of the Bird’s Head. We first summarise the stratigraphy of areas to the north and south of the Seram Trough highlighting those parts of the sequence relevant to this study.

Stratigraphy of Seram

The island of Seram can be divided geologically into two parts. A northern belt, covering the north part of the island in the west and all of it in the east, consists of imbricated sedimentary rocks of Triassic to Miocene age whose fossils and facies resemble those of the Misool and New Guinea continental shelf (Hamilton, 1979). The southern belt is dominated by low-grade metamorphic rocks. The stratigraphy of Seram summarised here (Figure 2) is based on published studies (Audley-Charles et al., 1979; O’Sullivan et al., 1985; Tjokrosapoetro and Budhitrisna, 1982).

The basement consists of high- to low-grade metamorphic rocks. The high-grade metamorphosed schists and gneisses of the Kobipoto Complex are probably Precambrian to Lower Palaeozoic. Palaeozoic rocks include phyllites and slightly metamorphosed shales, greywackes and limestone. The basement is overlain by Upper Triassic–Lower Jurassic dark grey siliciclastic sediments and limestones, some of which form parts of overthrust sheets. The Upper Jurassic to Upper Miocene Nief Beds were deposited after an interval of non-deposition and represent a shallowing upward sequence, from bathyal to nearshore. The sediments contain no terrigenous material and consist of foraminiferal limestones with a rich planktonic fauna. There was a period of non-deposition in the Middle Oligocene which was followed by the deposition of reefal limestone. The Nief Beds have been strongly deformed and thickened by thrusts verging to the northeast.

The thrustbelt of Mesozoic to Miocene sediments is covered unconformably by the Salas Block Clay, the Pliocene Wahai Beds and the Pleistocene Fufa Formation. The Salas Block Clay was first interpreted as an olistostrome similar to the Bobonaro Scaly Clay of Timor, although much thinner. It contains unsorted, angular, exotic blocks of all sizes and ages in a clay matrix and was dated as Late Miocene–Early Pliocene. However the mélanges of Timor have been reinterpreted as products of shale diapirism and mud volcanoes (Barber et al., 1986) and the Salas Block Clay may be similar. The Plio-Pleistocene section is about 3 km thick in north-central Seram. The mudstones and siltstones of the Wahai Beds were deposited in deep basins north of Seram and are strongly unconformable on the older strata. They are overlain by the deltaic Fufa Formation which consists of sands, conglomerates, limestone and reefal sediments.

Stratigraphy of Misool–Western Irian Jaya

The island of Misool is on the north flank of the Misool–Onin–Kumawa Anticlinorium (MOKA, Figure 1B) which plunges southeast towards the Onin peninsula of Irian Jaya. The stratigraphy of Misool and western Irian Jaya described here (Figure 2) is based on previously published schemes (Fraser et al., 1993; Pieters et al., 1983; Pigram et al., 1982; Pigram and Panggabean, 1981).

On Misool, there is the most complete Mesozoic stratigraphic sequence in SE Asia. The basement consists of probable metamorphosed turbidites. The metamorphic rocks are of uncertain age (Silurian to Devonian?) but consist of slates and phyllites similar
to those in the Bird’s Head and on the islands of Buru and Seram. On Misool the basement is overlain by a thick sequence of turbidites of Late Permian–Triassic age also similar to rocks on Seram. On Misool, a phase of block faulting and uplift in the Late Triassic changed the environment from deep water to a shallow marine reefal platform. Faulting was followed by a period of non-deposition and erosion. Marine sedimentation resumed in topographic lows in the Early Jurassic with the deposition of the Yefbie Shale on Misool which is calcareous shale and siltstone deposited in a restricted marine environment. It is overlain by marls and shales of the Jurassic Demu Formation and Lelinta Shale which mark the change to a deepwater open marine environment. The overlying Lower Cretaceous Facet Limestone Group is a bathyal limestone at the base, passing up into tuffaceous calcilutites, shales and marls reflecting contemporaneous volcanic activity to the north. The Upper Cretaceous Fafanlap Formation marks the transition to a fluviodeltaic environment and consists of calcareous siltstones, greywackes and shales.

In western Irian Jaya and the Bird’s Head there is a similar sequence to Misool. Fluvio-deltaic clastics of the Bird’s Head (Upper Carboniferous–Permian) are overlain by Triassic–Lower Jurassic shales and mainly continental sandstones contemporaneous with rifting. The same Late Triassic–Middle Jurassic breakup stage can be observed on Seram, Misool and Irian Jaya. The Toarcian–Bajocian Inanwatan Polysequence represents a nearshore setting passing progressively into fluviatile and lacustrine environments. The Callovian–Kimmeridgian Roabiba Polysequence followed a 12 Ma period of erosion or non-deposition. It consists mainly of claystones and limestones and represents a nearshore environment with little terrestrial influence. The Tithonian–Valanginian Sebyar Polysequence follows a major stratigraphic break and represents a major regional transgression. The Coniacian–Maastrichtian Jass Polysequence follows a major phase of erosion which occurred in the Albian or Aptian. A major transgression began in the mid Campanian which led to the deposition of deepwater argillaceous sediments. The sequence passes continuously into the Tertiary in western Irian Jaya but towards the west the uppermost Cretaceous sediments were eroded. The Jass Polysequence is interpreted as the facies equivalent of the Cretaceous Lower Nief Beds of Seram (Fraser et al., 1993). Throughout the region, waning clastic input from the Late Cretaceous led to the deposition of limestones and the Early Tertiary marked the reestablishment of a widespread carbonate regime. The Zaag Limestone of Misool and overlying formations (Kasim Marl, Openta Limestone and Atkari Limestone) show similar facies throughout the Tertiary and the whole section is equivalent to the New Guinea Limestone Group of Irian Jaya. On Misool, some units are separated by angular unconformities and paraconformities but sedimentation was more continuous in Irian Jaya. The Lower New Guinea Limestone is an oolitic and bioclastic foraminiferal shoal limestone equivalent to the Zaag Limestone of Misool. The Upper New Guinea Limestone is equivalent to the Kasim Marls and Openta Limestone of Misool and consists of mudstones overlain by reefal limestones. The New Guinea Limestone Group is also very similar in lithology to the Upper Nief Beds of Seram. The period of non-deposition in the Middle Oligocene on Seram is also represented on Misool. The Late Miocene was an important time of sedimentological change with a return to clastic sequences as indicated by deposition of thick mudstone and sandstone sequences. The Pliocene and Pleistocene Klasafet and Klasaman Formations reach a thickness of 5000 m in the Salawati basin and lie unconformably on top of the New Guinea Limestone.

DATA SET AND METHODOLOGY

The 2D time-migrated seismic data set was provided by TGS-NOPEC Geophysical Company and tied to seven key wells to the north of the Seram Trough (Figure 1B). Seven horizons were interpreted (Figures 2 and 3) and contoured. Because the wells are located to the north of the trough, the names of the deeper sequences mapped are based on the Bird’s Head stratigraphy (Fraser et al., 1993). The lower four horizons identified are: top Inanwatan (Middle Jurassic), top Jass (Paleocene), top Lower New Guinea Limestone (Late Oligocene) and top Upper New Guinea Limestone (Late Miocene). A major Early Pliocene unconformity separates these four units from three higher sequences which were also interpreted. As the upper sequences cannot be matched to stratigraphic units previously identified they are named from their appearance on the seismic lines: a transgressive sequence (TS) and two progradational sequences (PS1 and PS2). Time–thickness maps were produced between the Early Pliocene unconformity and the four horizons below.
The three upper sequences were studied in order to define better the timing of events associated with the development of the trough.

**STRUCTURAL–STRATIGRAPHIC EVOLUTION**

The seabed was mapped and contoured to identify the axis of the Seram Trough. The trough is deeper to the west (~ 5200 m) than to the east (~ 3500 m) and the north slope is steeper to the east of Misool.

**Mesozoic-Lower Pliocene Sequences**

Figure 3 is a NE–SW seismic line which ties the wells Agung–1, CS–1X and Daram South–1 (Figure 1B). At this point the trough is about 25 km wide. CS–1X and Agung–1 both reached the Permian and on this line the top of the Palaeozoic could be interpreted. However, it could not be traced over the whole survey as the reflector is discontinuous and difficult to pick. The Mesozoic sequences were not studied in detail but the following features can be observed. The Inanwatan Polysequence is generally thinner in the north of the area (Figure 3). Near the northern end of the seismic line it thickens towards normal faults and indicates a rifting event in the Early Jurassic. The top of the Jass Polysequence represents the Cretaceous–Tertiary boundary. Although the Roabiba, Sebyar and Jass Polysequences represent almost the entire Jurassic and Cretaceous, they are very thin (from 585 m in CS–1X to 80 m in Gunung–1). Well data shows the Roabiba and Sebyar Polysequences have been eroded in places but no obvious Mesozoic unconformity surface can be identified on the seismic lines. In contrast, the New Guinea Limestone Group of Paleogene and Neogene age is much thicker. When complete it is about 2350 m thick (in Gunung–1). The Lower New Guinea Limestone has been partially eroded to the south of Misool and the whole of the Upper New Guinea Limestone remains only in the Berau Basin (Figure 1B), elsewhere it has been partly or entirely removed by erosion.

The whole pre-Pliocene section and Pliocene of the Klasafet Formation have been deformed by open folds with amplitudes of several hundred metres, and wavelengths which vary from about 5 to 20 kilometres. These are truncated by a major unconformity (Figure 3) with a broad antiformal shape with the axis passing between wells Daram South–1 and CS–1X. The antiform has a half wavelength of the order of a hundred kilometres. The south limb dips more steeply, with an average dip of about 4°, than the north limb and is now covered by sediments in the trough. To the north three sequences can be recognised above the unconformity, the first of which onlaps onto it, and the upper two which clearly prograde towards the Seram Trough. The sediments south of the trough appear very complex in structure and must have been thrusted and folded after contraction started. Growth strata indicate contraction is still active (Figure 3).

In most wells, the formation immediately beneath the major unconformity is the Upper New Guinea Limestone. As this extends in age from the Late Oligocene into the Late Miocene it does not constrain the age of the unconformity very precisely. However, in the Berau Basin the Upper New Guinea Limestone is overlain by approximately 2 km (1 second TWTT) of younger rocks which were assigned to the Klasafet and Klasaman Formations in wells Onin North–1 and Gunung–1 (Figure 4). No unconformity was recognised in these wells. However, the unconformity can be traced on the seismic lines and clearly separates a sequence that was deposited conformably on top of the Upper New Guinea Limestone (and deformed with it) here assigned to the Klasafet Formation, from the undeformed progradational sequences above the unconformity. The depth of the unconformity surface interpreted from the seismic data was found to be 480 m below sea level in Onin North–1 and 400 m in Gunung–1. From the well stratigraphic data, the age of the unconformity was determined to be Early Pliocene. Pliocene strata are identified above and below the unconformity surface. An unconformity of this age has not been previously recognised. Perkins and Livsey (1993) are the only authors to have identified an unconformity in this region, but they did not date it.

**Folding of the Early Pliocene Unconformity**

An obvious palaeorelief can be observed in places south of Misool and along an elongate area running from the SE of Misool to the Onin Peninsula of Irian Jaya which is clearly an ancient land surface (Figure 5). The unconformity can be mapped easily to the north of the trough (Figure 6) but to the south the structure is much more complex and the unconformity surface could not be picked with certainty. Because of the extent of the unconformity, and the relatively limited topographic relief, it is reasonable to assume
that it was originally relatively flat and was mostly emergent. This is supported by the observation that the unconformity is an erosional surface even where it has been tilted into the trough (Figure 3); although in the trough the folds beneath the unconformity are gentle, the unconformity is seen to truncate the earlier sequences. Significant relief was probably produced where emergence was most prolonged although the strongest relief is present where the Tertiary New Guinea Limestone was exposed and could be the result of karstic dissolution.

The unconformity has been folded and now dips south towards the Seram Trough and north towards the Salawati Basin (Figure 6). Three zones were defined to describe the unconformity and the sequences above it, a Western, a Central and an Eastern Zone (Figure 6). In the Western Zone (south of Misool, the unconformity surface dips at a low angle (about 5°) towards the trough. In the Central Zone the unconformity surface changes suddenly from almost horizontal to dips of about 20° in the trough where it is covered by a greater thickness of sediments (about 3 km). In the Eastern Zone (adjacent to the Onin Peninsula of Irian Jaya), the dip of the unconformity surface returns to about 5°. The axial trace of the anticline folding the unconformity surface is parallel to the trough (Figure 6), which suggests that the two structures are related.

Time–thickness maps between the unconformity surface and the four horizons interpreted beneath were used to produce a subcrop map for the Pliocene unconformity (Figure 7). The top of the Upper New Guinea Limestone was removed over most of the area except in a depocentre to the east (the Berau Basin) where the full thickness of the formation remains. Sediments as old as Middle Jurassic (Inanwatan Polysequence) were exposed.

The central axis of the area of uplift produced by folding (Figure 7) runs sinuously from the south of Misool to the Onin Peninsula of Irian Jaya and is sometimes referred to as the Misool–Onin Anticlinorium (Fraser et al., 1993). The Klasafet Formation and Upper New Guinea Limestone have been completely removed over an area up to 30 km wide which extends for more than 200 km (Figure 7). Its orientation indicates that contraction was broadly NNE–SSW. This is consistent with the vergence of the folds observed on seismic lines. Faults beneath the unconformity appear to tip-out near the base of the folded New Guinea Limestone. Some retain clear extensional offsets in the lower Jass, Sebyar and Roabiba Polysequences suggesting that most of the folds were developed by inversion of older extensional faults. Deformation seems to have been more intense to the east of the area. The folds are tighter and better developed, and erosion removed sediments as old as Middle Jurassic beneath the unconformity. The area south of Misool was also exposed at the surface and the Upper New Guinea Limestone is missing, but folding of the pre-Pliocene section is more gentle. The tightest folds are in the region close to the anticlinorium hinge and folds are more open nearer to the trough. The trace of the anticlinorium defined by the folds beneath the unconformity surface differs from the axial trace of the fold defined by the unconformity surface itself, further indicating that the two phases of folding relate to separate events.

**Sequences Above the Unconformity**

Subsidence followed the Early Pliocene erosional stage, and to the north of the trough three distinct sequences are recognised above the unconformity. The sequence directly overlying the unconformity is transgressive as it onlaps the unconformity surface and is called the Transgressive Sequence (TS). The two youngest sequences are clearly progradational and are referred to as Progradational Sequence 1 (PS1) and Progradational Sequence 2 (PS2). In some parts of the survey, the sediments in the trough can be correlated with these sequences and are generally thicker in the east (up to 3 km thick in the Central Zone).

a. **Transgressive Sequence (TS)**

Subsidence led to the deposition of a transgressive sequence over most of the area except in the most elevated places (Figure 3). To the north, the sediments are flat and simply fill the pre-existing depressions (Figures 3 and 4), but towards the trough in the Western Zone the sediments appear to onlap the unconformity surface, which suggests that the unconformity was already slightly tilted prior to the transgression. However, the bedding is not perfectly horizontal (Figure 3), indicating that the unconformity was being tilted as TS was deposited.
In the Central and Eastern zones, TS can be traced into the trough showing that the sediments in the trough and those north of it are contemporaneous. In the Central Zone the internal structure of the sediments is disturbed above the slope break and has been interpreted as disrupted due to gravity slides. This suggests that tilting of the unconformity surface occurred quite suddenly and rapidly, or that tilting started earlier in this zone so that when TS was deposited, the slope was steeper and the sediments became rapidly unstable. This is consistent with the fact that the unconformity surface is now steeper in this zone and that the sediments in the trough are thicker there too, as noted above. In the eastern part of the Central Zone sediments in the trough onlap onto the unconformity and were later back-rotated, indicating that tilting of the unconformity surface started before those sediments were laid down and continued during their deposition.

In the Eastern Zone, TS also thickens towards the trough but is offset by several normal faults above the slope break. Tilting of the unconformity surface must have caused extension in the sediments being deposited above. Overall the sediments thicken to the south. As the unconformity was being tilted down towards the trough, accommodation space was increasing in this area, and therefore the sediments are thicker towards the trough.

b. First Progradational Sequence (PS1)

TS is overlain by a sequence which covers the whole area except above the high between the wells Daram South–1 and CS–1X (Figure 3). It was deposited horizontally in the north (Figures 3 and 4) but clearly progrades south towards the trough in the Western Zone (Figure 3). In the Central Zone, PS1 is composed of several parasequences. The progradation direction indicates a source to the NNE, and is consistent with increasing accommodation space to the south associated with the developing trough. The top of the sequence is horizontal across most of the area, indicating no further deformation of the Misool–Onin Anticlinorium after the deposition of PS1. Like TS, PS1 is contemporaneous with some of the sediments in the trough. Debris flow events and slumping seem to have occurred where the slope is steepest in the Central Zone and must have contributed to the accumulation of sediments in the trough. The thickness of the units above the Early Pliocene unconformity (up to 3 km) indicates a high sedimentation rate in the last 4 Ma. In the trough the top of PS1 corresponds to the base of the growth strata which developed during thrusting. This suggests that contraction started in the trough immediately after the deposition of PS1.

c. Second Progradational Sequence and Growth Strata (PS2)

PS2 is also clearly progradational (Figure 3) and is interpreted to be contemporaneous with the growth strata observed in the trough and hence with the start of contraction. It can be traced into the trough in the Eastern Zone but it is missing above the slope in the Western and Central zones, and was probably not deposited there as the slope was too steep. The structure south of the trough is very complex in the Western Zone (Figure 3) but in the Central and Eastern zones thrust faults can be identified more easily and they clearly detach at the unconformity surface. In the Eastern Zone contraction seems to have caused the faulting observed on the crest of the folds. Contraction in the trough is still active as the growth strata are overlain unconformably by sediments which are currently being deformed.

DISCUSSION

The new seismic data show that the Mesozoic sequences north of the Seram Trough overlie the metamorphic basement and are thin with numerous stratigraphic breaks but no angular unconformities. The Late Triassic–Early Jurassic rifting event corresponding to the breakup of the northern Gondwana can be identified on the north end of Figure 3 where the Inanwatan Polysequence thickens onto normal faults. Although a significant phase of erosion is described from the Aptian–Albian (Fraser et al., 1993) during a period of non-deposition of 50 Ma, no obvious unconformity surface can be recognised on the seismic lines, probably because it is not an angular discordance. The Tertiary sequence is conformable on older sequences. The Cenozoic New Guinea Limestone is thick (2.3 km when complete) and extends into the Upper Miocene. The Late Miocene marked the beginning of clastic input, represented by clays and occasionally fine sands, and
the sequence changes from pure carbonates of the New Guinea Limestone to neritic limestones and claystones of the Klasafet Formation. This may be a response to a global sea level fall (Haq et al., 1987).

The first important deformation event identified from the seismic lines is Early Pliocene in age. Contraction was broadly NE–SW and reactivated some older normal faults. This produced an anticlinorium running sinuously from SE of Misool to the Onin Peninsula of Irian Jaya. Large amplitude open folds are present in the central part of the anticlinorium, and to the north and south of this structure there are fewer folds which are more open. This study does not support the suggestion (Pigram and Panggabean, 1981) that the anticlinorium was produced by folding in the Late Oligocene. The only angular discordance seen on the seismic lines clearly post-dates the deposition of the Upper New Guinea Limestone and is seen to truncate part of the overlying Klasafet Formation. The anticlinorium axial trace is oblique to the Seram Trough. The folds also become more widely spaced and broader closer to the trough. Both these observations suggest that the Seram Trough and the anticlinorium are not related and were formed by two separate events. The irregular trace of the anticlinorium is possibly the result of reactivation of an old basement lineament (Fraser et al., 1993) or the inversion of extensional faults.

Folding was followed by a period of erosion in the late Early Pliocene which produced a major angular unconformity not previously recognised in the region. Erosion removed sediments as old as Middle Jurassic along the anticlinorium and in places the unconformity is clearly an ancient topographic surface. It now descends into the trough where it truncates the Upper New Guinea Limestone and in places cuts down to the Lower New Guinea Limestone. Strong relief is probably the result of subaerial karstic dissolution of the New Guinea Limestone with a maximum local relief of the order of a few hundred metres near the culmination of the anticlinorium. Over the rest of the region the unconformity was probably close to horizontal at the time of its formation. A second episode of very gentle folding warped the unconformity surface. South of the Misool–Onin anticlinal axis the unconformity surface now dips towards the trough and descends into the trough where it can be traced to depths of more than 6 km below sea level. The axis of this anticlinal structure is parallel to the Seram Trough.

A transgressive sequence was deposited over the unconformity surface. Transgression could in part be due to rising sea level but the thickness and depths of the sequence TS, PS1 and PS2 (more than 300 m water depths and up to 1 km of sediment) imply that renewed subsidence followed the Early Pliocene erosion phase and continues to the present. The oldest sediments present in the trough (TS) dip towards the trough axis and can be traced northwards into almost a flat-lying sequence at shallow depths on some seismic lines. On the north flank of the trough TS dips into the trough but also onlaps the unconformity surface suggesting that tilting of the unconformity towards the trough started during the deposition of TS. There are gravity slides and slumping in the Central Zone where the slope is steepest. Tilting may have started earlier in this zone or the amount of tilting may have been greater.

The transgressive sequence is overlain by two distinct sequences (PS1 and PS2) which are clearly progradational north of the break of slope. PS1 can be traced into the trough on most of the lines. The upper progradational sequence (PS2) can be traced into the trough on a few lines near the Onin Peninsula but on most lines PS2 is missing on the slope descending into the trough. This suggests that the trough became deeper with time and PS2 was probably not deposited on the flank of the trough because the slope became too steep. PS2 is interpreted to be contemporaneous with the start of contraction in the trough. Thrust faults in the trough appear to detach at the unconformity surface and seem to be younger in the Central and Eastern zones because the sediments in the trough are less deformed in these zones. Contraction is active at present as indicated by the presence of sequences of growth strata which reach the seabed.

**Summary of deformation history**

The sequence of events deduced from this study is as follows. The first deformation event occurred in the Early Pliocene and produced the Misool–Onin anticlinorium. Folding was followed by a period of erosion. The resulting unconformity surface was approximately horizontal and cuts down to sequences as old as Middle Jurassic. The unconformity surface was originally subaerial and is covered by a transgressive and then progradational sequences 1 km thick, all of which indicate significant later subsidence. The unconformity was folded and now
dips south towards the trough south of the anticlinal axis. Both subsidence and contraction in the trough post-date the unconformity surface and therefore convergence between Seram and New Guinea started more recently than the Late Miocene age previously suggested (Audley-Charles et al., 1979).

Tilting of the unconformity started during the deposition of the transgressive sequence and the slope became gradually steeper with time. The anticlinal axis of the unconformity surface is parallel to the trough, which suggests that tilting of the unconformity may have been caused by loading due to thrusting on Seram. This is consistent with the asymmetry of the trough which is steeper on its southern side (Figure 3). Longitudinally, the trough is deepest to the west, immediately north of Seram, in front of the most elevated parts of the island. Together these observations imply that the Seram Trough is a foredeep associated with thrusting, and the folded unconformity surface to the north is a peripheral bulge. East of Seram the area south of the trough is below sea level and the trough is correspondingly shallower since the load is less.

**Relationship to deformation on Seram**

On Seram thrusting caused repetition of sequences of Mesozoic to Miocene age. Thrust faults probably detach at their contact with metamorphic basement, or within Triassic turbidites (de Smet and Barber, 1992). Rapid uplift due to thrusting caused simultaneous erosion, which led to the deposition of the clastics of the Plio-Pleistocene Wahai and Fufa Formations. These are strongly unconformable on top of the thrustbelt of Mesozoic–Miocene sediments (Audley-Charles et al., 1979). This means that the detachment surface must cut through the Mesozoic–Miocene section somewhere between Seram and the trough.

Sometime between the Late Pliocene and the present, loading on Seram produced a foredeep at the location of the trough and the anticlinal fold of the unconformity surface observed on the Misool shelf was caused by uplift at the bulge. Figure 8 is an evolutionary diagram illustrating this model: the sequences on the Misool shelf were uplifted to the north while they were tilted in the foredeep. Because tilting of the unconformity surface is a direct response to thickening and loading in Seram, the three sequences above the unconformity on the Misool shelf are interpreted to be contemporaneous with the Salas Block Clay and Wahai and Fufa Formations of Seram. Contraction continued as the foredeep was being filled, and younger thrusts started to develop in the basin itself towards the current location of the trough, hence deforming the sediments just deposited (Figure 8D).

In the deepest part of the trough north of Seram the sediments overlying the unconformity in the trough itself are much thinner than in the Central and Eastern zones. In these two zones the northern slope of the trough is steeper and on the slope there is less sediment above the unconformity (TS, PS1 and PS2). These observations suggest that sediment is being carried into the trough from the northern slope, little is reaching the trough from Seram, and sediment from Seram is presumably being trapped in the perched basins above the developing thrust belt.

The foredeep model accounts for most observations, although a few points are still problematic. One would expect the bulge to migrate northwards following the direction of thrusting. However, there is no sign that the bulge (characterised by the anticlinal fold of the unconformity surface) has migrated. Furthermore the unconformity surface has subsided since it was produced and is now covered by up to 1 km of sediment above the anticlinal axis (Figure 3). The variation in steepness of the northern slope of the trough is not directly related to the depth of the trough; it is steeper where the trough is less deep which suggests some variation in strength of the lithosphere along the trough. Tandon et al. (2000) have shown that variations in bathymetric profiles along the Timor Trough may be accounted for by variations in effective elastic thickness of the flexing plate.

**CONCLUSIONS**

The Seram Trough in eastern Indonesia has been the subject of controversy as to whether it is a subduction trench or simply a zone of intraplate shortening. This study of new seismic lines shot across the Seram Trough favours a foredeep model although a subduction origin cannot be completely excluded. There is no evidence of strike-slip faulting. The shallow depth of the trough, 5200 m maximum between Misool and Buru decreasing eastwards into the study area to a depth of 3500 m, is much less than most subduction trenches. The similarities in stratigraphy between Seram and Misool–New Guinea
also support the foredeep model rather than subduction. There was folding in the Early Pliocene which produced the Misool–Onin anticlinorium. A regional Early Pliocene unconformity not previously known truncates sediments as old as Middle Jurassic and clearly is an ancient topographic surface with significant relief in places. The unconformity surface was later folded and now dips south towards the trough where it is covered by sediments as thick as 3 km. The anticlinal axis of the unconformity surface is parallel to the Seram Trough. North of the trough, the sediments above the unconformity can be divided into three distinct sequences which were deposited as the unconformity was being folded. Tilting of the unconformity surface started with the deposition of a transgressive sequence. The two overlying sequences prograde towards the trough and the upper progradational sequence is contemporary with the growth strata observed in the trough and with thrusting in the trough. Thrust faults in the trough deform the sediments deposited above the unconformity and clearly detach at the unconformity.

However, on Seram thrusting repeats sections of Mesozoic–Miocene sediments. This implies that the detachment surface is cutting up-section between Seram and the trough. Contraction between Seram and New Guinea post-dates the Early Pliocene unconformity and is therefore younger than the previously suggested Late Miocene age.

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Figure 1 - A: Tectonic map of the Banda Arc, eastern Indonesia. Large arrows represent Australia–Pacific and Australia-Eurasia relative plate motions (DeMets et al., 1994). B: Location of the seismic lines and wells. MOKA: Misool–Onin–Kumawa Anticlinorium.
Figure 2 - Stratigraphy of Misool and Irian Jaya (north of the trough) and Seram (south of the trough).
Figure 3 - NE-SW seismic line and interpretation across the Seram Trough. Pre-Pliocene sequences are deformed, and truncated by a major unconformity. The unconformity surface has a broad anticlinal shape and dips steeply towards the south. It is overlain to the north by three sequences, of which the two uppermost prograde towards the trough. To the south the structure is complex, and sediments must have been deformed by contraction between Seram and New Guinea.
Figure 4 - The top of the Upper New Guinea Limestone is preserved and the unconformity has been dated as Early Pliocene from the wells indicated on the section.

Figure 5 - The Early Pliocene unconformity is discordant and resembles an ancient land surface in places south of Misool and along a high running from the east of Misool to the Onin Peninsula of Irian Jaya. Relief is strongest in places where the Lower New Guinea Limestone was exposed and is interpreted to be the result of karstic dissolution.
Figure 6 - Time-structure map of the Early Pliocene unconformity surface. The unconformity dips more steeply towards the trough, and is deeper, in the Central Zone. Depths in ms.

Figure 7 - Subcrop map of the Pliocene unconformity. The axial trace of the anticline folding the unconformity surface is parallel to the Seram Trough, which suggests it is the result of loading caused by thrusting on Seram.
Figure 8 - Evolution of the foredeep. A: Contraction started after the Early Pliocene unconformity was produced. B and C: Tilting of the unconformity started during the deposition of the transgressive sequence, and the slope became steeper with time. D: Contraction continued as the foredeep was being filled and younger thrusts started to develop in the basin itself, hence deforming the sediments just deposited.