Structural styles and tectonic evolution of the Seram Trough, Indonesia

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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 of New Guinea and Seram Island. It has been interpreted as a subduction trench, an intra-continental thrust zone and foredeep, and a zone of strike-slip faulting. Recently acquired 2D seismic lines clarify its tectonic evolution and relationship to the Bird’s Head. Folding in the Early Pliocene formed an anticlinorium running from Misool to the Onin Peninsula of Irian Jaya and produced a newly recognised angular unconformity. The 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 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. The Seram Trough is interpreted to be a very young zone of thrusting within the Australian continental margin.

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1. Introduction

The Seram Trough is located between the islands of Seram and Misool to the west of New Guinea (Irian Jaya or West Papua) in East Indonesia (Fig. 1A). East 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 principally of sedimentary, metamorphic and some igneous rocks 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 Miocene. 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, Barber, Charlton, Klemperer, & Hussong, 1987) interpret it as a subduction zone separating the Australian and Eurasian plates whereas others (e.g. Audley-Charles, 1986; Tandon, Lorenzo, & O’Brien, 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, Helmers, & Sopaheluwakan, 1997; Milsom, Audley-Charles, Barber, & Carter, 1983) although 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 & Isacks, 1978; McCaffrey, 1989).

2D seismic surveys shot along the Seram Trough (Fig. 1B) by TGS-NOPEC Geophysical Company in 1998.

Fig. 1. A: Tectonic map of the Banda Arc, eastern Indonesia. Large arrows represent Australia–Pacific and Australia-Eurasia relative plate motions from (DeMets, Gordon, Argus, & Stein, 1994). B: Location of the seismic lines and wells. MOKA: Misool–Onin–Kumawa Anticlinorium.
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 the character and significance of the Seram Trough, and to identify the sequence of events which led to its development.

2. Present and past tectonic setting

After Timor, Seram is the second largest island (approximately 400 × 75 km²) of the outer Banda arc with mountains which reach heights of more than 3 km above sea level. The elevation of the island is a reflection of convergence between Seram and the Bird’s Head. The similarities of geology and palaeomagnetic data (Klootwijk et al., 1987; Thrupp, Sliter, Silver, Prasetyo, & Coe, 1987) suggest little relative motion during the Cenozoic between the Bird’s Head and the rest of New Guinea, which forms part of the Australian plate. However, GPS measurements show that the Bird’s Head is currently moving with the Pacific plate (Puntodewo et al., 1994; Stevens et al., 2002) and convergence rates at the Seram Trough are approximately 20 mm/a (Rangin et al., 1999; Stevens et al., 2002).

The region beneath Seram and south of the Seram Trough is one of intense shallow seismicity (Engdahl, van der Hilst, & Buland, 1998; McCaffrey, 1989) and fault plane solutions indicate active thrusting (McCaffrey, 1989). Southwest of Seram earthquake hypocentres can be traced to depths of more than 300 km suggesting a slab which dips to the south. It is debated if this slab is part of the Australian plate, or another plate. Some authors (e.g. Audley-Charles, Carter, Barber, Norvick, & Tjokrosapoetro, 1979; Hamilton, 1979) have suggested the Australian plate is being subducted beneath both the north and south Banda Arc, whereas others (e.g. Bowin et al., 1980; Cardwell & Isacks, 1978; McCaffrey, 1989; McCaffrey & Abers, 1991) have suggested that two different plates are being subducted beneath the north and south Banda Arc from the Seram and Timor Troughs respectively. Stevens et al. (2002) suggested the slab subducting beneath Seram is not oceanic lithosphere but continental lithosphere of the Bird’s Head which has resulted in the deepest subducted continental crust known on Earth.

Many of those who advocate a one slab or two slab model interpret Seram as the product of subduction. Hamilton (1979) and Bowin et al. (1980) regarded the subduction trench as being continuous along the Timor–Tanimbar Trough, the Aru Trough and the Seram Trough whereas O’Sullivan, Pegum, and Tarigan (1985) interpreted a second south-dipping slab beneath Seram. All interpreted the southern slopes of the Seram Trough as an accretionary wedge and described the island of Seram as a Tertiary subduction melange and imbricated complex. However, the island is formed largely of Australian rocks of sedimentary origin and Audley-Charles et al. (1979) suggested Seram was a mirror image of Timor and formed after arc-continent collision. The Timor Trough and Seram Troughs are interpreted (Audley-Charles, 1986; Audley-Charles et al., 1979) to have developed as a result of loading produced by overthrusting of the volcanic arc onto the Australian margin forming a foredeep. In Seram this was suggested to have occurred in the Late Miocene implying the existence of an older volcanic arc which collided with the Australian margin south of Seram.

3. Stratigraphy of the region

The Seram Trough separates Seram from the island of 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 the areas to the north and south of the Seram Trough.

3.1. 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 presented in this paper (Fig. 2) is based on previously published work (Audley-Charles et al., 1979; O’Sullivan et al., 1985; Tjokrosapoetro & Budhirnis, 1982).

On Seram, 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. Other Palaeozoic rocks are metamorphic: a Lower Palaeozoic Taunusa Complex (Tjokrosapoetro & Budhirnis, 1982), the Upper Palaeozoic Tehoru Formation phyllites which show multiple phases of deformation (Audley-Charles et al., 1979), and the pre- to Middle Triassic Kaibobo Complex, also called the Saku Formation, consisting of slightly metamorphosed shales, graywackes and limestone (Hartono & Tjokrosapoetro, 1984).

The basement is overlain by the Upper Triassic–Lower Jurassic dark grey siliclastic sediments of the Kanikeh Formation (also called the Wakuku Beds by Audley-Charles et al., 1979). These were deposited in a calm and moderately deep marine environment (Audley-Charles et al., 1979) although O’Sullivan et al. (1985) attributed them to a shallower near-shore environment. The age of the formation overlaps with that of the Saman-Saman Limestone which consists of laminated calcareous marls with moulds of radiolarians, interbedded with recrystallised calcilutites.
suggested to have been deposited in deep water beyond the shelf, based on the absence of clastic material (Audley-Charles et al., 1979). The Upper Triassic to Lower Jurassic Anisepe Limestone (called the Manusela Formation by O’Sullivan et al., 1985) is a reefal oolitic and bioclastic grainstone which was deposited in a warm and shallow marine environment. The formation forms several overthrust sheets which have been interpreted to have Asian affinities (Audley-Charles et al., 1979). 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 near-shore (Audley-Charles et al., 1979; O’Sullivan et al., 1985). The sediments contain no terrigenous material and consist of foraminiferal limestones with a rich planktonic fauna and chert nodules at the base. 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 (Audley-Charles et al., 1979).

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 (Audley-Charles et al., 1979) 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 to be the products of shale diapirism and mud volcanoes (Barber, Tjokrosapoetro, & Charlton, 1986) due to overthrusting or rapid sedimentation. Shale diapirs associated with mud volcanoes are present in eastern Seram and the Salas Block Clay probably has a similar origin.

The Plio-Pleistocene section is about 3 km thick in north-central Seram. The mudstones and siltstones of the Wahai Beds were deposited in the deep Wahai and Bula basins north of Seram and are strongly unconformable on the older terrain. The Wahai Beds are overlain by the deltaic Fufa
Formation which consists of sands, conglomerates, limestone and reefal sediments.

3.2. Stratigraphy of Misool–Western Irian Jaya

The island of Misool is the north flank of an anticlinorium plunging southeast towards the Onin peninsula of Irian Jaya known as the Misool–Onin–Kumawa Anticlinorium (MOKA, Fig. 1B). The stratigraphy of Misool and western Irian Jaya described here (Fig. 2) is based on previously published lithostratigraphic schemes (Fraser, Bon, & Samuel, 1993; Pieters et al., 1983; Pigram, Challinor, Hasibuan, Rusmana, & Hartono, 1982; Pigram & Panggabean, 1981) and a Mesozoic stratigraphy now commonly used in exploration using polysequences (Fraser et al., 1993), i.e. groups of sediment packages, each of which represents a depositional cycle. The stratigraphy is similar to the northwestern Australia margin rift-drift sequence and was controlled by the breakup of northern Gondwana and subsequent spreading in the Indian Ocean. On Misool, there is the most complete Mesozoic stratigraphic sequence in SE Asia.

The basement consists of probable metamorphosed turbidites. The Ligu metamorphic rocks of Misool are of uncertain age (Silurian to Devonian?) but consist of slates and phyllites similar to those in the Bird’s Head (Kekum Formation) and on the islands of Buru and Seram.

The basement is overlain by the clastic sediments of the Keskin Formation on Misool and by the Aifam Group and Tipuma Formation in Irian Jaya. The Keskin Formation is a thick sequence of turbidites of Late Permian–Triassic age similar in lithology to the Kanikeh Formation of Seram and probably represents an Australian siliciclastic shelf/basin facies. The carbonaceous clastics of the fluvio-deltaic Aifam Group in the Bird’s Head (Upper Carboniferous–Permian) might be in part a shallow water equivalent. The Aifam Group is overlain by Triassic–Lower Jurassic red-green shales and sandstones of the Tipuma Formation (mainly continental sediments) which are contemporaneous with initial rifting.

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 where the Bogal Limestone was deposited. Faulting was followed by a period of non-deposition and erosion caused by a global sea level fall which removed the Aifam Group and Tipuma Formation from some highs in parts of Irian Jaya. The same Late Triassic-Middle Jurassic breakup stage can be observed on Seram, Misool and Irian Jaya.

Marine sedimentation resumed in topographic lows in the late Early Jurassic with the deposition of the Yefbie Shale on Misool. The Yefbie Shale of Misool is a grey 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 deep-water open marine environment. The overlying Lower Cretaceous Facet Limestone Group is a bathyal limestone with chert nodules at the base, passing up into highly tuffaceous calcilutites, shales and marls reflecting contemporaneous volcanic activity to the north. The Upper Cretaceous Fafanlap Formation marks the transition to a fluvo-deltaic environment and consists of calcareous siltstones, greywackes and shales.

In western Irian Jaya there is a similar sequence to Misool. The Lower Toarcian to Upper Bajocian Inanwatan Polysequence represents a near-shore setting passing progressively into fluvial and lacustrine environments. The Upper Triassic–Lower Jurassic Saman-Saman Limestone of Seram is interpreted (Fraser et al., 1993) as the facies equivalent of the Inanwatan Polysequence. The Lower Callovian to Lower Kimmeridgian Roabiba Polysequence followed a 12 Ma period of erosion or non-deposition. It consists mainly of claystones and limestones and represents a near-shore environment with little terrestrial influence. The Mid-Tithonian to Lower Valanginian Sebyar Polysequence follows a major stratigraphic break and represents a major regional transgression. The Coniacian to Maastrichtian Jass Polysequence followed a major phase of erosion which occurred in the Albion or Aptian. A major transgression began in the mid Campanian which led to the deposition of deep-water argilaceous 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 Kljasafet and Klasaman
Formations reach a thickness of 5000 m in the Salawati basin and lie unconformably on top of the New Guinea Limestone.

4. 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 (Fig. 1B). Seven horizons were interpreted (Figs. 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.

5. Structural-stratigraphic evolution

The seabed was mapped and contoured in order to determine precisely the location of 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.

5.1. Mesozoic-Lower Pliocene sequences

Fig. 3 is a NE-SW seismic line which ties the wells Agung-1, CS-1X and Daram South-1 (see Fig. 1B for location). At this position of this line 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 (Fig. 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 show 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 (see Fig. 1B for location); elsewhere it has been partly or entirely removed by erosion associated with a major unconformity.

5.2. Early Pliocene unconformity

The whole pre-Pliocene section has been deformed by gentle to open folds with amplitudes of several hundred metres, and wavelengths which vary from about 5 to 20 km. Faults beneath the unconformity appear to tip-out near the base of the folded New Guinea Limestone (Fig. 7). Some retain clear extensional offsets in the lower Jass, Sebyar and Roabiba Polysequences suggesting that many of the folds were developed by inversion of older extensional faults, some of which are completely inverted. Contraction produced an anticlinorium running sinuously from the SE of Misool to the Onin Peninsula of Irian Jaya. The tightest folds are in the region close to the anticlinorium hinge, and folds are more open nearer to the trough as illustrated by Figs. 7 and 9. Deformation seems to have been more intense to the east of the area where true-scale sections show that the folds are tighter and better developed (Fig. 9).

These structures are truncated by a major unconformity (Fig. 3) with a broad antiformal shape which has an axis passing between wells Daram South-1 and CS-1X. The antiform has a wavelength of the order of two hundred kilometres. The south limb has an average dip of about 4°, dips more steeply than the north limb, and is now covered by sediments in the trough. The orientation of the antiform indicates that contraction was broadly NNE-SSW. This is consistent with the vergence of the folds observed on seismic lines. Erosion removed sediments as old as Middle Jurassic beneath the unconformity.

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; all that can be said is that the unconformity is Late Miocene or younger. However, in the Berau Basin the Upper New Guinea Limestone is overlain by approximately 2 km (1 s TWTT) of younger rocks assigned to the Klasafet and Klasaman Formations, which range in age from Late Miocene to Recent, in wells Onin North-1 and Gunung-1 (Fig. 4). No unconformity was previously recognised in these wells as there is no major time break and only a small discordance which would not be evident during drilling. However, on seismic lines the unconformity can be clearly traced through the Klasafet and Klasaman clastic sequence and separates a part 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 change to clastic sedimentation occurred some time before the folding event and formation of the unconformity since there is up to one kilometre of Klasafet Formation sediments.

The depth of the unconformity surface within the Klasafet and Klasaman Formations clastic sequence identified from the seismic data is 480 m below sea level in Onin North-1 and 400 m in Gunung-1 which permit its age to be determined. There are also some limits on the age of the unconformity from biozones identified in wells Daram South-1 and Onin South-1. From the detailed biostratigraphic data and the well time-depth curves, the unconformity can be dated as late Early Pliocene, and is no older than 4 Ma using the Berggren, Kent, Swisher, and Aubry (1995) timescale. 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.

5.3. Erosion associated with the Early Pliocene unconformity

Folding in the Early Pliocene was followed by a period of erosion. 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 (Fig. 10A). An obvious palaeo-relief 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 (Fig. 5). The unconformity can be mapped easily to the north edge of the trough (Fig. 6) but south of here the structure becomes much more complex and the unconformity surface could not be picked with certainty. Because of the extent of the unconformity, the gentle to open style of the folds beneath it, and the relatively limited topographic relief compared to the dimensions of the anticlinorium, it is clear that the unconformity was
Fig. 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. Vertical exaggeration approximately × 5.

Fig. 6. Time-structure map of the Early Pliocene unconformity surface (4 Ma). The unconformity dips more steeply towards the trough, and is deeper, in the Central Zone. Depths in ms.
originally almost flat and was probably mostly emergent. The unconformity is an erosional surface even where it has since been tilted into the trough (Figs. 3 and 8). Although in the trough the folds beneath the unconformity are gentle, the unconformity is seen to truncate the earlier sequences (Figs. 7 and 9). Significant relief was probably produced where emergence was most prolonged.

The strongest relief is evident where the Tertiary New Guinea Limestone was exposed and is likely to be the result of karstic dissolution.

Time–thickness maps between the unconformity surface and the four horizons interpreted beneath were used to produce a subcrop map for the Pliocene unconformity (Fig. 10). This shows the areas which suffered the greatest
amount of erosion, removing more than one kilometre of section. 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. The area south of Misool was exposed at the surface and the whole of the Upper New Guinea Limestone is missing (Fig. 7). In places, sediments as old as Middle Jurassic (Iinanwatan Polyequence) were exposed at the time.

5.4. Deformation of the unconformity after the Early Pliocene

The sequences overlying the unconformity show that the unconformity was later folded and it now dips south towards the Seram Trough and north towards the Salawati Basin (Fig. 6). The central axis of the area of uplift produced by folding (Fig. 10) 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 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.

Three zones were defined to describe the unconformity and the sequences above it, a Western, a Central and an Eastern Zone (Fig. 6). In the Western Zone (south of Misool, Fig. 7), the unconformity surface dips at a low angle (about 2°) towards the trough, and 6° within the trough. In the Central Zone (Fig. 8) the unconformity surface changes suddenly from almost horizontal/slightly dipping to dips of about 10° 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, Fig. 9), the dip of the unconformity surface returns to 3° towards the trough, and remains at 10° within the trough. The axial trace of the anticline folding the unconformity surface is parallel to the trough (Fig. 6), which suggests that the two structures are related.

5.5. Sequences post-dating the Early Pliocene unconformity

Subsidence followed the Early Pliocene erosional stage, and three distinct sequences are recognised above the unconformity. The sediments south of the trough are very complex in structure and must have been thrusted and folded after contraction started. Growth strata indicate contraction is still active (Fig. 3). However, north of the trough the situation is more straightforward. The sequence directly overlying the unconformity is transgressive as it onlaps the unconformity surface and is here called the TS. The two youngest sequences are clearly progradational and are referred to here 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).

5.6. Transgressive sequence

Subsidence led to the deposition of a TS over most of the area except in the most elevated places (Fig. 3). To the north, the sediments are flat and simply fill the pre-existing depressions (Figs. 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 parallel (Figs. 3, 10 and 11A), indicating that the unconformity was being tilted as TS was deposited.

In the Central and Eastern zones, TS can be traced into the trough (Figs. 9 and 11B) showing that the sediments in the trough and those north of it are contemporaneous. In the Central Zone (Fig. 8) the internal structure of the sediments is disturbed above the slope break and is 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 (Fig. 11C), sediments in the trough onlap 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 (Fig. 9). 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 tilting down towards the trough, accommodation space was increasing in this area, and therefore the sediments are thicker towards the trough.

5.7. 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 (Fig. 3). It was deposited horizontally in the north (Figs. 3 and 4) but clearly progrades south towards the trough in the Western Zone (Figs. 3 and 11A). In the Central Zone (Figs. 8 and 11B), 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
Fig. 8. Central Zone: the slope of the unconformity surface changes suddenly from horizontal in the north to steeply dipping in the south. The unconformity clearly is an erosional surface, even in the trough, suggesting it formed close to sea level or was emergent. Gravity slides occurred during the deposition of TS. PS1 is divided into several parasequences of which one is progradational. PS2 is contemporaneous with growth strata in the trough where thrust faults detach at the unconformity surface. Vertical exaggeration approximately \( \times 3.5 \). Below interpretation is water-depth corrected seismic line.
Fig. 9. Eastern Zone: the unconformity surface dips more steeply than in the Western zone, but less than in the Central zone. TS and PS1 thicken towards the trough. Deformation below the unconformity was most intense in this zone. TS is offset by several normal faults which must have developed due to the progressive tilting of the unconformity surface. Contraction in the trough produced extensional faults on the crest of the folds. Vertical exaggeration approximately $\times 2$. Below interpretation is water-depth corrected seismic line.
the Misool-Onin Anticlinorium after the deposition of PS1. Like TS, PS1 is contemporaneous with some of the sediments in the trough (Fig. 11B). Debris flow events and slumping seem to have occurred where the slope is steepest in the Central Zone (Figs. 8 and 11C) 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 (Fig. 11C). This suggests that contraction started in the trough immediately after the deposition of PS1.

5.8. Second progradational sequence and growth strata (PS2)

PS2 is also clearly progradational (Figs. 3, 8 and 11) and is interpreted to be contemporaneous with the growth strata observed in the trough and hence with the start of contraction (Figs. 8 and 11C). It can be traced into the trough in the Eastern Zone (Fig. 9) 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 (Fig. 3) but in the Central and Eastern zones (Figs. 8 and 12) thrust faults can be identified more easily and they

fig. 10. A: 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. B: Cross-section along the line indicated showing the anticlinal structure. Vertical exaggeration approximately \( \times 6 \).
Fig. 11. A: Detail of the three sequences overlying the unconformity. TS onlaps but is tilted as well, indicating that tilting of the unconformity started before TS was deposited, and continued while it was laid down. B: TS and PS1 appear to form continuous units with the oldest sediments in the trough. Sediments in the trough are therefore contemporaneous with the sequences north of the break of slope. PS1 is divided into several parasequences. C: the oldest sediments in the trough onlap onto the unconformity and were later back rotated, indicating the unconformity was already tilted before their deposition, and was tilted further while they were laid down. A debris flow event occurred during the deposition of PS1. PS2 is contemporaneous with growth strata in the trough. Deformation in the trough started very recently. Vertical exaggeration approximately × 4 in all sections.
Fig. 12. Seismic lines and interpretation of A: Central Zone and B: Eastern Zone. The top of the sediments contemporaneous with PS1 is also the base of the growth strata, which suggests that contraction in the trough started during the deposition of PS2. The growth strata in B are overlain unconformably by younger sediments that are currently being deformed. Thrust faults in the trough are very clear in the Central and Eastern zones and detach at the unconformity surface. To the south of the trough, the structure becomes very complex (A).
clearly detach at the unconformity surface. In the Eastern Zone (Fig. 9) contraction seems to have caused the faulting observed on the crest of the folds. Contraction in the trough is still active as shown on Fig. 12B: the growth strata are overlain unconformably by sediments which are currently being deformed.

6. Discussion

The new seismic data help to determine the timing and character of deformation in the Seram Trough and northwards towards the Bird’s Head.

6.1. Mesozoic–Cenozoic sedimentation

Mesozoic sequences north of the Seram Trough overlie the metamorphic basement and are thin with numerous stratigraphic breaks but no angular unconformities. The final stage of the Late Triassic-Early Jurassic rifting event corresponding to the breakup of the northern Gondwana can be identified on the north end of Fig. 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 there is no 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. The change to clastic sedimentation occurred some time before the first deformation event since there is approximately one kilometre of neritic limestones and claystones of the Klasafet Formation below the unconformity. The change may be a response to a global sea level fall in the Late Miocene (Haq, Hardenbol, & Vail, 1987).

6.2. Early deformation

The first important deformation event identified from the seismic lines occurred in the Early Pliocene. Contraction was broadly NE–SW and reactivated some older normal faults. The area south of Misool was elevated but not so strongly folded as the eastern part of the study area where contraction produced an anticlinorium running sinuously from the 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 and these are more open. This study does not support the suggestion (Pigram & 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 (about 4 Ma) which produced a major angular unconformity. An unconformity of Early Pliocene age has not previously been 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. It may have been emergent or may have formed near sea level over most of the region. Strong relief is probably the result of karstic dissolution of the New Guinea Limestone. However, the maximum local relief is of the order of a few hundred metres in the region of the culmination of the anticlinorium and over the rest of the region the unconformity was probably close to horizontal at the time of its formation.

6.3. Younger deformation

A second episode of very gentle folding has 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 TS 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 an almost 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 TS 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 much more disturbed. East of Seram the area south of the trough is much less deformed in these zones. Contraction is active at present as indicated by the presence of sequences of growth strata which reach the seabed.

6.4. 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 which are one kilometre 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 TS 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 (Fig. 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 anticlinal fold of the unconformity surface to the north is a peripheral bulge. Contraction and deformation also seems to have been more important in this area as the structure south of the trough is much more disturbed. East of Seram the area south of the trough is below sea level and the trough is correspondingly shallower since the load is less.

6.5. 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 the shales and sandstone turbidites of the Triassic Kanikeh Formation (de Smet & 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 thrust belt 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. Fig. 13 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 described above the unconformity on the Misool shelf would be contemporaneous with the Salas Complex 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 (Fig. 13D).

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 been migrating. Furthermore the unconformity surface has subsided since it was produced and is now covered by up to 1 km of 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.

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7. Conclusions

The Seram Trough in eastern Indonesia has been the subject of controversy as to whether it is a subduction trench, a zone of intraplate shortening or a strike-slip zone. 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 (IOC, IHO,


& BODC, 1997) 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 is a regional Early Pliocene unconformity which was not known previously. This angular unconformity was produced by erosion following a folding event which occurred during the early Pliocene (approximately 4 Ma) and produced the Misool–Onin anticlinorium. The unconformity 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 folded 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 TS. The two overlying sequences prograde towards the trough and the upper progradational sequence is contemporaneous 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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References


Fig. 3. NE-SW seismic line, geo-seismic interpretation and water-depth corrected seismic line across the Seram Trough. Vertical exaggeration approximately $\times 8$. Pre-Pliocene sequences are deformed, and truncated by a major unconformity. The unconformity surface has a broad anticlinal shape and dips at about 5° 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.