Tertiary syntectonic carbonate platform development in Indonesia

MOYRA E. J. WILSON*, DAN W. J. BOSENCE† and ALEXANDER LIMBONG‡
*Department of Geological Sciences, Durham University, South Road, Durham DH1 3LE, UK (e-mail: moyra.wilson@durham.ac.uk)
†Geology Department, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK
‡Geological Research and Development Centre, Jalan Diponegoro, Bandung, Indonesia

ABSTRACT

Cenozoic tropical carbonate sedimentation was strongly influenced by local and regional tectonics in SE Asia. This paper outlines the evolution of the syntectonic Eocene to middle Miocene Tonasa Formation of South Sulawesi, evaluating controls on sedimentation, facies distribution and sequence development. Development of a facies model for this Cenozoic tropical carbonate platform provides a meaningful analogue for similar, less well-studied SE Asian carbonates, which commonly comprise targets for hydrocarbon exploration. This study also has considerable implications for the study of syntectonic carbonates, controls on carbonate sedimentation, carbonate platform development in backarc areas and SE Asian tectonics. Detailed facies mapping, logging, petrographic and biostratigraphic analyses indicate that the Tonasa Formation was deposited initially as part of a transgressive sequence in a backarc setting. By late Eocene times, shallow-water carbonates were being deposited over much of South Sulawesi forming a widespread (100-km long) platform area. Shallow-water sedimentation continued unabated in some areas of the platform until the middle Miocene. Elsewhere, active normal faulting resulted in fault-block platforms, with local subaerial exposure of footwall blocks and the formation of basinal graben in adjacent hangingwall areas. Platform-top facies were aggradational and dominated by larger benthic foraminifera. Low-angle slopes, particularly hangingwall dip slopes, were characterized by the development of ramps. Faults, controlled in part by pre-existing structures, were periodically active and formed steep escarpment margins. Variable regional subsidence strongly influenced the development of the Tonasa Carbonate Platform, whereas platform-wide effects caused by regional eustacy have not been identified. Computer modelling of the Tonasa Platform confirms that the accommodation space and sedimentary geometries observed can be produced by block faulting and regional subsidence alone. Modelling also reveals that regional subsidence and extension, oblique to the main stretching direction, were low on the margins of the backarc basin. Shallow-water accumulation rates for this foraminifera-dominated tropical carbonate platform were an order of magnitude lower than those for modern warm-water platforms dominated by corals or ooids.

Keywords Carbonate platform, computer modelling, facies, fault block, Indonesia, sequence development, syntectonic, Tertiary.
INTRODUCTION

Cenozoic carbonate production was extensive and diverse in the shallow tropical seas of SE Asia. This area was extremely active tectonically throughout the Cenozoic as a result of the interaction of three major plates (Indo-Australian, Eurasian and Pacific plates; Fig. 1). Carbonate successions developed in a range of tectonic settings, such as on microcontinental blocks, around the margins of extensional backarc basins and in forearc settings. Many platforms were influenced by tectonics or located on basement highs related to earlier structures, and SE Asia is one of the best areas of the world in which to study Cenozoic syntectonic carbonate platforms. However, there are few published facies models for these volumetrically and economically important carbonates. This paper aims to: (1) develop a facies model for, and document the evolution of, the previously unstudied Eocene to middle Miocene Tonasa Carbonate Platform of South Sulawesi; (2) evaluate factors influencing sedimentation on this syntectonic platform; (3) use a stratigraphic forward computer modelling program to determine whether a combination of tectonic subsidence and block faulting could have generated the accommodation space and geometries observed on this tilt-block carbonate platform.

The data for this research were gleaned from extensive facies mapping, logging and petrographic and biostratigraphic work throughout the outcrop area of the Tonasa Formation (Figs 2 and 3; Wilson, 1995). The facies and history of the northern faulted margin have been documented by Wilson & Bosence (1996) and Wilson (1999). Facies of the central platform and southern ramp-type margin are detailed in Wilson & Bosence (1997). Wilson (2000) details factors influencing the demise of the platform. This paper is the first to document the evolution and controls on sedimentation of the entire platform, integrating additional data from complexly faulted areas to the east and west of the main tilt-block platform.

In addition to providing a facies model for a tropical platform, analogous to many others in the region, this research has implications for syntectonic carbonates, carbonate development behind volcanic arcs and regional SE Asian tectonics. Computer modelling of this carbonate platform reveals information on production and
accumulation rates of tropical foraminifera-dominated systems, which were common in the past, but are now rare. Tectonic stretching factors and regional subsidence rates are also obtained for the margins of this backarc basin. A comparison is made between the Tonasa Carbonate Platform and other syntectonic platforms, and with similar outcrop and subsurface examples of SE Asian carbonates.

TECTONOSTRATIGRAPHIC SETTING OF SOUTH SULAWESI

The Cenozoic evolution of Sulawesi is linked to the accretion of microcontinental and oceanic material onto the eastern margin of Sundaland, the stable cratonic margin of Asia (Fig. 1), and to the resultant development of volcanic arcs. Western Sulawesi was accreted to Sundaland during the Cretaceous. Subduction and accretion in eastern Sulawesi occurred throughout the Cenozoic (Sukamto, 1975; Hamilton, 1979). Western Sulawesi, neighbouring east Borneo, and the East Java Sea were affected by widespread extensional basin formation beginning during the Early Palaeogene (Fig. 1; van de Weerd & Armin, 1992; Wilson & Moss, 1998). The Tonasa Carbonate Platform therefore developed in an extremely active tectonic area, on a microcontinental block at the eastern margin of an extensional basin and to the west of a volcanic arc.

South Sulawesi has an almost complete stratigraphic succession extending from the late Cretaceous to the present day, with carbonate deposits spanning much of the Tertiary (Fig. 2, Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981). During the late Cretaceous, deep marine clastics and shales of the Balangbaru/Marada Formations were deposited over tectonically
intersliced metamorphic, ultrabasic and sedimentary basement lithologies in western South Sulawesi (Fig. 2; van Leeuwen, 1981; Hasan, 1991). These sediments are inferred to have been deposited in a forearc setting to the west of a west-dipping subduction zone (Hasan, 1991). By Eocene times, subduction had moved further to the east, and marginal marine siliciclastics of the Malawa Formation, passing transgressively upwards into carbonates of the Tonasa Formation, were deposited in western South Sulawesi. During the deposition of these sedimentary units, lithologies in eastern South Sulawesi were dominated by volcaniclastic and igneous rocks of the Salo Kalupang, Langi and Kalamiseng Formations (Sukamto, 1982; Yuwono et al., 1987). The Eocene/Oligocene igneous lithologies are thought to be the products of a subduction-related calcalkaline volcanic arc, whereas the Kalamiseng Formation may be an ophiolitic sequence, accreted during the Oligo/

Miocene (Yuwono et al., 1987). The Tonasa Formation is overlain by volcaniclastic deposits of the Camba Formation, derived from a volcanic arc, which developed in western Sulawesi in the middle to late Miocene (Fig. 2; Yuwono et al., 1987).

**STRATIGRAPHIC FRAMEWORK OF THE TONASA CARBONATE PLATFORM**

The early/middle Eocene to middle Miocene Tonasa Formation was deposited mainly in western South Sulawesi (Fig. 2). Larger benthic foraminifera dominated shallow-water deposits of the extensive Tonasa Carbonate Platform. These organisms provide good palaeoenvironmental and biostratigraphic indicators and were used for platform-wide correlation [Fig. 2; cf. East Indian Letter Classification (EILC) after Adams, 1970]. In areas of good three-dimensional exposure, such as the Barru area, visual correlation of sequences was also possible. Deeper water deposits were dated with planktonic foraminifera and nannofossils. Other bioclasts include coralline algae, echinoid fragments, small benthic foraminifera and rare coral debris.

The Tonasa Formation includes up to 600 m of shallow-water, platform-top lithologies in the central Pangkajene area (Fig. 3). Over a kilometre of shallow-water lithologies overlain by basinal deposits were deposited to the north (Barru area) and south (Jeneponto area, Figs 3–7). The Tonasa Carbonate Platform had a north–south extent of about 100 km. From late Eocene times, the platform was bounded by a steep, but segmented, faulted northern platform margin and a gently dipping ramp-type southern margin (Fig. 7; Wilson & Bosence, 1996, 1997). Areas of more complex block faulting lay to the west (Fig. 7; Segeri area) and east (Fig. 9; Western Divide area). Detailed analysis of platform and basinal deposits reveals that the Tonasa Carbonate Platform was affected by a number of phases of syndepositional tectonic activity (van Leeuwen, 1981; Wilson & Bosence, 1996).

A summary of the changes in depositional environment, nature of the margins and lateral extent of the Tonasa Carbonate Platform are documented below. These are presented together with palaeogeographic maps (Fig. 4), chronostatigraphic (Fig. 5) and lithostratigraphic (Fig. 6) correlations, reconstructions and cross-sections through the platform (Figs 7 and 8).
Fig. 4. Simplified palaeogeographic maps of South Sulawesi from the early/middle Eocene to the middle Miocene during the deposition of the Tonasa Formation. Not rotated for palaeomagnetic data.
**PALAEOGEOGRAPHIC EVOLUTION OF THE CARBONATE PLATFORM**

**Early/middle Eocene (Ta)**

Palaeogene marginal-marine clastics of the Malawa Formation and volcanioclastics of the Langi Volcanics pass transgressively and rapidly upwards into shallow-marine carbonates of the Tonasa Formation in the western and eastern parts of South Sulawesi respectively (Fig. 2). Carbonate sedimentation began diachronously in South Sulawesi, initially during the early to middle Eocene in the northern Barru area (Figs 4 and 5). Well data, 10 km offshore south-west Sulawesi (well ODB-1X; Fig. 4), also suggest that early to middle Eocene carbonate sedimentation occurred in the southern Jeneponto area. However, the base of the Tonasa Formation does not outcrop in the Jeneponto area, and the oldest exposed rocks are middle to late Eocene packstones.

In the northerly Barru area, the basal few metres of the carbonate succession contain clastic grains and interdigitate with marginal marine clastics of the Malawa Formation. A variety of skeletal wackestone, packstone and grainstone lithologies indicate that early carbonate sedimentation developed in a range of shallow-marine environments. Abundant *Potamididae* gastropods (Fig. 8A) and rare calcite pseudomorphs after gypsum or anhydrite in some initial carbonate deposits suggest locally restricted conditions. However, the presence of larger perforate foraminifera (Fig. 8B) and rare corals in all other initial carbonate sediments indicate dominantly stenohaline conditions. East- to west-trending grainstones (Fig. 8B) and packstones (Fig. 8C) containing abundant robust, and commonly fragmented, larger benthic foraminifera are interpreted as moderate- to high-energy shoal deposits. Wackestones and packstones accumulated in lower energy intervening areas.

The oldest sediments exposed in the southerly Jeneponto area are well-bedded bioclastic packstones. These contain abundant planktonic foraminifera and fragmented or whole, shallow-water bioclasts and are interpreted as middle to
Fig. 7. North–south block diagram through the tilt-block platform of the Tonasa Formation showing the central Pangkajene, northern Barru, southern Jeneponto and western Segeri areas during the Oligocene. The distribution of biota across the platform is also shown.
outer ramp deposits with an open oceanic influence (Wilson & Bosence, 1997).

**Late Eocene (Tb)**

During the late Eocene, carbonate sedimentation spread to the Pangkajene (Crotty & Engelhardt, 1993), Segeri and Western Divide areas (Figs 4 and 5). Minor interdigititation with underlying formations in these areas suggests slight diachroneity in the initiation of carbonate sedimentation. Late Eocene lithologies in the Pangkajene and Western Divide areas consist of larger benthic foraminifera grainstones, packstones and wackestones. A broad platform area composed of shoals, channels and intervening lower energy regions, all within the photic zone, is the inferred depositional setting for these areas. Late Eocene foraminiferal carbonates outcrop at Maborongnge to the east of the Walanae Depression (Figs 2 and 3). However, it is not clear whether shallow-water deposits of the Tonasa Carbonate Platform extended laterally across this area, or if isolated shoals developed around the volcanic arc in eastern South Sulawesi. Palaeocurrent data from the central part of the Pangkajene area indicate that the dominant transport direction was towards the east (Wilson & Bosence, 1997).

In the northern Barru area, carbonate sedimentation during the early part of the late Eocene continued as a series of shoals, trending E–W, with lower energy intervening areas as described above. In areas that later developed into hanging-wall graben, such as the Rala section, shallow-water carbonates are at their thickest and deepen upsection (Fig. 6). The laterally equivalent deposits in areas that later formed foothill highs, such as the Doi-doi and Bangabangae sections, are thinner and do not deepen upwards. This suggests increased differential subsidence for developing hangingwall areas during fault propagation (Wilson, 1999). Correlatable bioclastic packstone and grainstones units, with many containing planktonic foraminifera (Fig. 8D), overlie the shallow-water deposits described above from the Barru area. These deposits are also of late Eocene age and indicate an upsequence deepening to open-marine outer-shelf and slope deposits in the northern part of the Barru area. From the appearance of quartz only on developing foothill highs and variations in sequence thickness, these deposits are interpreted as a latest prerift/earliest synrift sequence. A thick sequence of late Eocene basal marls sharply overlies the bioclastic units in the northern part of the Barru area (Fig. 8E). The marls are interbedded with coarse redeposited facies containing a variety of limestone and siliciclastic, metamorphic and igneous lithic clasts from the underlying formations of South Sulawesi. These redeposited units were derived from major active normal faults bordering the Tonasa Carbonate Platform (Wilson & Bosence, 1996). The configuration of the northern margin of the Tonasa Carbonate Platform was a segmented escarpment margin (Fig. 7), where the faults were periodically active from the latest late Eocene through to the middle Miocene.

In the Segeri area, late Eocene deposits are composed of a thin sequence of shallow-marine packstones and grainstones, containing abundant larger benthic foraminifera. Marls interbedded with redeposited carbonate facies sharply overlie the shallow-water deposits (Fig. 5). This abrupt drowning, the textural immaturity of redeposited facies, together with karstified shallow-water clasts derived from adjacent areas, all suggest active block faulting similar to the Barru area. Other possible evidence for late Eocene block faulting comes from the Western Divide area. Shallow-marine carbonates in the Bantimala, Malawa West, Ujunglamuru and Maborongnge sections (Figs 3 and 5) were subaerially exposed and tilted during or after the late Eocene and before the middle Miocene. In comparison, in the nearby Bua and Biru sections (Figs 3 and 5), late Eocene carbonate facies show no evidence for karstification and instead deepen upsection.

The background sedimentation in the southerly Jeneponto area is of basinal marls (Wilson & Bosence, 1997). However, unlike the Barru and Segeri areas, there is no evidence for major shedding of syntectonic redeposited units into this basinal area. In contrast, mid- to outer-ramp shelf/slope packstones of the southern margin of the Tonasa Carbonate Platform prograded southwards into basinal deposits at least twice during the late Eocene (Figs 5 and 6). Sharp contacts between the basinal marls and packages of bioclastic packstones, traceable over a few kilometres, suggest that progradation was rapid.

**Oligocene (Tc–T_{e1–4})**

Dominantly aggradational sequences of Oligocene shallow-water foraminifera wackestone, packstones and grainstones are exposed throughout much of the Pangkajene area. The presence of abundant planktonic foraminifera in the upper part of the Bulo Kamase section indicates that open oceanic conditions influenced the south-
western part of the Pangkajene area during the latest late Oligocene (Fig. 6). However, this is the only evidence for flooding of open-marine waters onto the top of the main platform throughout its history. Through the Oligocene and perhaps the latest late Eocene, facies belts trended east–west on the platform top. Mudstone and wackestone facies dominated in the northern and southern parts of the Pangkajene area (Figs 6 and 8F), suggesting regions of shallow to moderate depths in the photic zone with low to moderate energy. Small coral patch reefs developed only in the southern part of the Pangkajene area. In contrast, moderate- to high-energy conditions are inferred for the central part of the Pangkajene area based on the predominance of grainstones and pack-
The dominance of east-directed palaeo-currents suggests that the northern and southern parts of the Pangkajene area were protected and sheltered by some form of barrier (Fig. 7). Evidence for Oligocene intertidal sedimentation and possible subaerial exposure and karstification are found only in the northern part of the Pangkajene area (Figs 5 and 6).

In the Western Divide area, Oligocene deposits are exposed only along the eastern flank of the Bantimala Block and in the Biru area (Figs 5 and 9; van Leeuwen, 1981). Shallow-water deposits in these localities have been subaerially exposed and eroded during the early/?late Oligocene. In the Biru area, packstones and grainstones overlying a brecciated horizon, thought to be caused by exposure, contain planktonic foraminifera, indicating an open-marine influence during the late Oligocene/early Miocene (van Leeuwen, 1981).

The Tonasa Carbonate Platform was bordered by an escarpment margin in the Barru area, and deeper basinal marl sedimentation took place to the north (Fig. 7). Shedding of coarse, immature redeposited facies may be related to a period of active normal faulting during the early/late Oligocene (Figs 5 and 6), although a relative sea-level change cannot be ruled out (Wilson & Bosence, 1996). Thick sequences of Oligocene marls interbedded with fine redeposited carbonate facies indicate that the Segeri area was also a region of deeper water sedimentation (Fig. 5). It is not clear whether late Eocene basin-bounding faults were still active in this area. Well-bedded packstones of Oligocene age in the Jeneponto area suggest that mid- to outer-ramp deposits of the southern margin of the Tonasa Carbonate Platform again prograded southwards into basinal deposits (Figs 5–7; Wilson & Bosence, 1997).

Fig. 9. Schematic reconstructed section through the Western Divide area, just before the deposition of the Camba Formation in the middle Miocene. Section passes through Birau, Camba and Biru (Fig. 3). Note that the figure is shown with 20 × vertical exaggeration.

© 2000 International Association of Sedimentologists, *Sedimentology, 47*, 395–419
Miocene (Te5–Tf)

Miocene deposits in the Pangkajene area were found only in the uppermost parts of southerly and south-westerly Bulo Kamase and Patunuang Asue sections (Fig. 6). In the Bulo Kamase section, abundant planktonic foraminifera in some beds indicate an open oceanic influence. In comparison, the larger benthic foraminifera packstones and grainstones in the Patunuang Asue section indicate shallow-water, moderate-energy shelf conditions (Fig. 5). In this section, marginal-marine coals, volcaniclastic siltstones and sandstone of the Camba Formation conformably overlie the carbonates (Wilson, 1999).

The variety of carbonate lithologies in the Western Divide, Barru and Segeri areas, including larger benthic foraminifera packstones, marls and redeposited carbonate facies, indicates a range of early/middle Miocene shallow- to deeper water environments (Fig. 5). In the deeper water areas in the Barru and Western Divide sections, marls are interbedded with thick beds of coarse, texturally immature clast-supported breccias, suggesting tectonic instability and block faulting (Wilson & Bosence, 1996). In the Segeri area, coarse redeposited units are rarely interbedded with Miocene marls, and passive basin infill is inferred to have occurred. On block-faulted highs adjacent to graben in the Western Divide and Segeri areas, shallow-water carbonates were subaerially exposed and tilted in the Miocene (Fig. 8G).

Some Miocene shallow-water carbonate production and subaerial exposure is inferred for the northern Barru and southern Jeneponto areas during the early/middle Eocene. During the late Eocene, carbonate sedimentation had spread to all areas of exposure of the Tonasa Formation. The late Eocene was a period of widespread foraminifera-dominated platform carbonate sedimentation and was the time when the Tonasa Carbonate Platform had its greatest areal extent. Faulting and segmentation of this broad carbonate platform affected the Barru and Segeri areas during the latest late Eocene and continued into the early Oligocene (Figs 5 and 7). Deep marine graben or half-graben, which persisted through to the Miocene, formed as a result of this faulting, and there was local subaerial exposure of adjacent footwall highs. From the latest Eocene to middle Miocene, deeper water areas were situated to the north, west and south of the main shallow-water carbonate platform. This platform had a tilt-block morphology with a gently sloping southern ramp-type margin and a faulted northern margin, which was periodically active (Fig. 6). The early to middle Miocene was a period of widespread block faulting, affecting most areas of the Tonasa Formation. Marginal-marine and marine volcaniclastic deposits of the Camba Formation were deposited over an irregular surface with variable submarine and subaerial topography.

Carbonate sedimentation in the Barru and Jeneponto areas initially developed as land-attached shelves (sensu James & Kendall, 1992) to the north and south of a land/marginal-marine area and to the west of a volcanic arc. Larger benthic foraminifera shoals and intervening areas, dominated by finer carbonate sediments, formed on these low-relief carbonate shelves and the subsequent, more extensive late Eocene carbonate platform. A ramp-type margin developed in the Jeneponto area. Given the lack of framework builders in in situ or reworked shallow-water deposits of the Tonasa Formation, accretionary rimmed margins (cf. Read, 1985) seem unlikely for the other unexposed seaward margins of the carbonate sequence or a change in slope is inferred from the low-angle unconformity between the Tonasa and Camba Formations.

FACIES MODEL AND STRATIGRAPHIC EVOLUTION OF THE TONASA PLATFORM

Initial sediment accumulation within the Tonasa Formation was diachronous and began in the northern Barru and southern Jeneponto areas during the early/middle Eocene. During the late Eocene, carbonate sedimentation had spread to all areas of exposure of the Tonasa Formation. The late Eocene was a period of widespread foraminifera-dominated platform carbonate sedimentation and was the time when the Tonasa Carbonate Platform had its greatest areal extent. Faulting and segmentation of this broad carbonate platform affected the Barru and Segeri areas during the latest late Eocene and continued into the early Oligocene (Figs 5 and 7). Deep marine graben or half-graben, which persisted through to the Miocene, formed as a result of this faulting, and there was local subaerial exposure of adjacent footwall highs. From the latest Eocene to middle Miocene, deeper water areas were situated to the north, west and south of the main shallow-water carbonate platform. This platform had a tilt-block morphology with a gently sloping southern ramp-type margin and a faulted northern margin, which was periodically active (Fig. 6). The early to middle Miocene was a period of widespread block faulting, affecting most areas of the Tonasa Formation. Marginal-marine and marine volcaniclastic deposits of the Camba Formation were deposited over an irregular surface with variable submarine and subaerial topography.

Carbonate sedimentation in the Barru and Jeneponto areas initially developed as land-attached shelves (sensu James & Kendall, 1992) to the north and south of a land/marginal-marine area and to the west of a volcanic arc. Larger benthic foraminifera shoals and intervening areas, dominated by finer carbonate sediments, formed on these low-relief carbonate shelves and the subsequent, more extensive late Eocene carbonate platform. A ramp-type margin developed in the Jeneponto area. Given the lack of framework builders in in situ or reworked shallow-water deposits of the Tonasa Formation, accretionary rimmed margins (cf. Read, 1985) seem unlikely for the other unexposed seaward margins of the carbonate sequence or a change in slope is inferred from the low-angle unconformity between the Tonasa and Camba Formations.
shelf/platform. During and after fault segmentation of this extensive platform, low-angle margins, particularly on the dipslope of hangingwall blocks, are characterized by ramps lacking framework builders. Steeper platform margins developed as fault-bounded erosional or escarpment margins. These differ from other modern or Miocene tropical rimmed platforms, even those that formed as fault-bounded margins, in that reefal carbonates or high-energy shoals did not develop. This is because of the domination of larger benthic foraminifera and a lack of framework-building organisms, inferred to be caused at least in part by biogeographic isolation (Wilson & Rosen, 1998). This model of carbonate platform development appears to be applicable to other Palaeogene carbonate platforms throughout SE Asia (cf. Adams, 1965; Kohar, 1985; Siemers et al., 1992).

**Table 1. Summary of factors affecting morphology and sedimentation on the Tonasa Carbonate Platform.**

<table>
<thead>
<tr>
<th>Controls</th>
<th>Platform morphology</th>
<th>Sedimentation and stratigraphic succession</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tectonism</strong></td>
<td>Active faulting and subsidence. Tilt-block morphology and block-faulted areas.</td>
<td>Regional subsidence creating accommodation space. Instability and exposure of basement lithologies. Tilting resulting in local exposure or drowning.</td>
</tr>
<tr>
<td><strong>Climate</strong></td>
<td>Tropical climate throughout deposition. Equatorial setting – no aridity, no coated grains or associated evaporites or dolomites.</td>
<td>Tropical biogenic carbonate production. Prevailing wind direction – distribution of facies.</td>
</tr>
<tr>
<td><strong>Eustacy</strong></td>
<td>Effects difficult to recognize, but may include progradation of ramp-type southern margin.</td>
<td>May have influenced metre-scale cycles in shallow-water facies.</td>
</tr>
<tr>
<td><strong>Organisms</strong></td>
<td>No extensive frameworks as larger benthic foraminifera dominated.</td>
<td>Larger benthic foraminifera dominated wackestones, packstones and grainstones.</td>
</tr>
<tr>
<td><strong>Terrigenous or nutrient input</strong></td>
<td>Distant from terrigenous input (effectively isolated platform). Low nutrient levels control the type of organisms found on the Tonasa Carbonate Platform.</td>
<td>Local exposure and subsequent reworking of siliciclastics from underlying formations due to faulting.</td>
</tr>
<tr>
<td><strong>Oceanography</strong></td>
<td>Oceanic circulation patterns and position of windward shoals/islands along the windward margin affected platform-top morphology.</td>
<td>Oceanic circulation resulted in east–west facies belts on the main tilt-block platform. Mostly normal marine facies, minor restriction.</td>
</tr>
<tr>
<td><strong>Volcanism</strong></td>
<td>Inferred volcanic arc to the east of South Sulawesi may have limited the eastern extent on the Tonasa Carbonate Platform. Middle Miocene volcanic arc smothered remaining carbonate-producing areas in Sulawesi.</td>
<td>Little visible effect on carbonate platform sedimentation. Contributed to the demise of the Tonasa Carbonate Platform.</td>
</tr>
<tr>
<td><strong>Autocyclicity</strong></td>
<td>Upbuilding of shallow-water platform deposits.</td>
<td>Platform-top facies belts remained relatively stable through time. Influenced metre-scale cycles in shallow-water facies?</td>
</tr>
<tr>
<td><strong>Basement structures</strong></td>
<td>Syndepositional faults, whose location may be related to basement structures, resulted in tilt-block morphology and areas of more complex block-faulting.</td>
<td>Affected accommodation space.</td>
</tr>
</tbody>
</table>
surfaces suggest that eustacy and autocycliclity were not major influences on the development of the platform. For these same reasons, together with problems of precise correlation of platform and basinal facies related to lack of exposure of the platform margins, a sequence stratigraphic approach to evaluating the evolution of the platform was not practical. Salinity fluctuations, nutrient and terrigenous input had little effect on carbonate development, and the Tonasa Carbonate Platform can effectively be regarded as an open-marine isolated platform from the late Eocene onwards. Volcanic activity limited the eastward lateral extent of carbonate sedimentation and played a role in the demise of the carbonate platform.

**Regional subsidence**

Maximum thicknesses of 1100, ~600, >1000 and 350 m for the Tonasa Formation were deposited in the Barru, Pangkajene, Jeneponto and Western Divide areas respectively (Figs 6 and 9). Regionally variable subsidence, related to a combination of crustal flexure and block faulting, was therefore the primary control on the production of accommodation space for the carbonate succession. In areas of faulting, particularly along the segmented, faulted northern margin of the main platform, variable rates and amounts of subsidence were caused by local differential subsidence, before and during faulting. For example, over a distance of 5 km in the Barru area, the correlatable Eocene latest prerift sequence thins from over 300 m to between 50 and 200 m in areas that later developed into hangingwall depocentres (Rala) and footwall highs (Doi-doi; Fig. 6) respectively. The late Eocene to middle Miocene synrift sequence reaches its maximum thickness of 635 m in hanging-wall depocentres (Rala section). However, this sequence is not present, or only a few tens of metres thick, on adjacent footwall highs (Fig. 6).

In the Pangkajene area, the three main E- to W-trending shallow-water facies belts appear to have been dominantly aggradational through the Oligocene and part of the late Eocene. Although there was some eastward progradation of sediments in the central facies belt, there is no evidence for north–south lateral progradation of facies belts. Aggradation of up to 600 m of shallow-water carbonates again indicates that subsidence was the dominant control on accommodation space.

**Block faulting**

During the late Eocene, the extensive shallow-water Tonasa Carbonate Platform was segmented by normal faults. Subsequently, shallow-water sedimentation continued unabated on footwall highs or local subaerial exposure; non-deposition or erosion occurred in areas adjacent to faults. In contrast, in downthrown blocks, there is a sharp change from shallow-water carbonates to basinal marls, caused by rapid fault-controlled subsidence, during the late Eocene in the Barru and Segeri areas, and during the early Miocene in parts of the Western Divide area.

Thick sequences of coarse, texturally immature redeposited carbonate facies are interbedded with basinal marls in graben or half-graben in the Barru, Segeri and Western Divide areas. The redeposited facies contain a range of shallow-water carbonate clasts, clasts from underlying formations and sometimes un lithified shallow-water bioclasts, all derived from syntectonic footwall highs and reworked into hangingwall depocentres. The range of clasts present reflects the variability of carbonate facies across the original carbonate platform, and the lithological differences of the 'basement' in the various fault blocks (cf. Martini et al., 1986; Wilson & Bosence, 1996). In the Barru area, redeposited facies are juxtaposed against older formations across at least two offset NW- to SE-trending normal faults, with throws of hundreds of metres, which bounded the northern margin of the main platform (Fig. 7). The Western Divide area is inferred to have been a complex region of block faulting from at least the early Miocene (Fig. 9).

The timing of drowning and generation of associated syntectonic redeposited facies indicate phases of rapid fault-controlled subsidence in the Barru, Segeri and Western Divide areas during the late Eocene to earliest Oligocene and early to middle Miocene (Fig. 5). In hangingwall depocentres in the Barru area, three phases of coarse redeposited facies formed, with the lower and upper units related to the main periods of faulting (above). The middle Oligocene redeposited facies may also be related to active faulting along the northern margin of the Tonasa Carbonate Platform. However, a eustatic cause or eustatic enhancement of a tectonic control is impossible to rule out for these facies, particularly as they contain a higher proportion of un lithified shallow-water bioclasts than the lower and upper units.

The main Tonasa Carbonate Platform had a syndepositional faulted northern margin and a

© 2000 International Association of Sedimentologists, *Sedimentology, 47*, 395–419
gently sloping ramp-type southern margin, and was a large-scale syntectonic tilt-block platform during the late Eocene to middle Miocene (Fig. 7). The platform succession thickens down the hangingwall dipslope into the Jeneponto area. Although changes in subsidence during block rotation may have caused progradation on the southern ramp-type margin, difficulties of correlation make this impossible to prove (see computer modelling section below).

Antecedent topography and basement structures

Active faulting affected the Tonasa Carbonate Platform in the late Eocene to early Oligocene and early/middle Miocene. Seismic data from the East Java Sea indicate that Cretaceous compressional faults were reactivated during the Eocene, and then again during the Miocene (Letouzey et al., 1990; Bransden & Matthews, 1992). Lithological variation and changes in the stratigraphic thickness of Cretaceous and Paleogene clastic successions in South Sulawesi suggest that pre-Tertiary structures also controlled differential subsidence and the location of faulting during the deposition of the Tonasa Formation. Carbonate sedimentation first developed in the early/middle Eocene in the Barru and Jeneponto areas (Fig. 5). This diachronality may be related to antecedent topography as well as to differential subsidence. The presence of siliciclastic grains only in the basal few metres of the shallow-water deposits of the Tonasa Carbonate Platform suggests that local basement highs, if they existed, had low relief and were quickly buried.

Climate, organisms and oceanography

South Sulawesi was located in a tropical setting throughout the Tertiary. Benthic foraminifera and sometimes coralline algae were the dominant carbonate-producing organisms on the platform. Coated grains such as ooids are absent, and corals are rare. The dominance of larger benthic foraminifera resulted in low rates of carbonate production compared with modern coralgal tropical carbonates (see computer modelling below). The biota and predominance of calcareous sands and muds would have affected the facies distribution and ‘keep-up’ potential, and reduced resistance to reworking by currents, waves and storms on the platform. The morphology of the Tonasa Carbonate Platform and its margins, particularly the western margin, are inferred to have modified cross-platform currents. The central part of the Pangkajene area was swept by easterly directed cross-platform currents, as indicated by palaeo-current data, and high-energy facies dominate (Wilson & Bosence, 1997). In comparison, northern and southern sequences in the Pangkajene area are composed of lower energy facies, and shoals or islands to the west of these localities are inferred to have deflected and dissipated cross-platform currents (Fig. 7).

COMPUTER MODELLING

The effects of relative sea-level changes on a carbonate platform with a tilt-block morphology, such as the main Tonasa Platform, will vary systematically in response to regional sea-level changes or block rotation (Fig. 10). Note that contemporaneous sedimentation on different parts of a tilt-block platform undergoing faulting and rotation may appear to occur in relative highstand, transgressive, regressive or lowstand settings (Fig. 10). This illustrates the difficulties in applying sequence stratigraphic methodology to study syntectonic platforms (Gawthorpe et al., 1994; Bosence et al., 1996). The main north- to south-trending tilt-block platform of the Tonasa Formation was clearly syntectonic with active faulting along the northern margin, at least during the late Eocene to earliest Oligocene and early to middle Miocene. Forward computer modelling (cf. Bosence et al., 1998) of the tilt-block platform was undertaken to determine whether it would have been possible to generate the available accommodation space and observed geometries of the platform by block faulting, block rotation and regional subsidence alone. Owing to problems of accurate platform-wide correlation, particularly across non-exposed platform margins, it is impossible to relate the observed progradation of the southern ramp-type margin directly to periods of tectonic quiescence or possible regional relative sea-level fall (Fig. 10). However, eustacy is unlikely to have been the primary influence generating progradation of the southern ramp-type margin of the Tonasa Carbonate Platform, given the lack of a discernible platform-wide eustatic influence and the strong tectonic overprint.

For the results of the forward modelling to be valid, a number of criteria had to be fulfilled, as identified from the fieldwork:

1. stratigraphic thicknesses, lateral extents and depositional environments should match those observed in key sections;
Fig. 10. Schematic diagram showing various possible effects of tilt-block rotation resulting from active normal faulting and relative sea-level change on the deposition of a carbonate platform with a tilt-block morphology. For the effects of regional sea-level change, the diagram is shown as evolutionary to illustrate the relative changes in platform morphology and sedimentation under different sea-level states. On the Tonasa Carbonate Platform, precise correlation between deposits derived from the steep northern margin and on the gently dipping southern margin is impossible, and marginal deposits are not preserved/exposed. Coarse redeposited facies derived from the steep northern margin of the Tonasa Carbonate Platform are inferred to result from normal faulting. The effects of relative sea-level change and controls on dipslope shallow-water sedimentation are difficult to determine.
(2) the hangingwall depocentre in the Barru area had to be drowned rapidly as a result of faulting, and the area should remain as a deep marine basin;

(3) the platform top had to remain an area of dominantly aggradational shallow-water sedimentation, with no platform-wide unconformities or marine flooding surfaces;

(4) rapid progradation of the southern ramp-type margin had to occur during phases of tectonic quiescence.

Computer modelling techniques

The computer program used for forward modelling the development of carbonate tilt-block platforms combined elements of the CARBONATE and DOMINO programs developed by Hardy & Waltham (1992), and is described by Bosence et al. (1998). Within this modelling program, it is possible to vary parameters, such as fault-block width, initial fault dip, phases of extension with specified beta values and thickness of prerift strata (Fig. 11). The program automatically adjusts for water and sediment loading, crustal thinning and thermal relaxation using given crustal and lithospheric thicknesses and densities (Waltham et al., 1993). To model carbonate sedimentation, a carbonate stratigraphy is deposited by the program as a series of lines (in this case, every 2 Myr), which are colour coded for depth of deposition and angle of slope (Fig. 11). Carbonate sediment is produced at specified rates (m kyr\(^{-1}\)) at five different water depths, based on comparison with modern analogues or other well-constrained outcrop studies (Bosence et al., 1994). Negative production rates are used above sea level to account for dissolution and erosion. Highest production rates occur in water depths of less than 20 m, and production rates decrease to pelagic production rates of about 0.1 m kyr\(^{-1}\) at the base of the photic zone (Fig. 11). A diffusion parameter is used to simulate erosion and slope failure related to subaerial or submarine topography, such as across steep platform margins. The main parameters varied during this modelling were timing, amounts and rates of extension, regional subsidence and carbonate production rates. Variables such as fault width (120 km), fault dip (75\(^\circ\)) and prerift thickness (1.5 km) were input from field data. Detailed information on

Fig. 11. Best fit, unique, forward computer model solution for a north–south section through the tilt-block Tonasa Carbonate Platform. The upper diagram shows no vertical exaggeration, and the lower diagram is at 4 \(\times\) vertical exaggeration to highlight platform-top sedimentation. The parameters used are shown.
crustal and lithospheric thicknesses and densities are lacking for South Sulawesi, and standard values for attenuated continental crust were used. The program models two-dimensional slices through carbonate tilt-block platforms and cannot account for lateral variations related to segmentation of the main north-bounding fault to the Tonasa Carbonate Platform. For this reason, a north- to south-trending transect, approximately perpendicular to the main northern faulted margin, avoiding areas of complex faulting and platform segmentation passing through the Rala, Tonasa-II, Lapangan Golf, Patunuang Asue and Jeneponto sections, was chosen as the best transect to model (Figs 7 and 11). Also, given the two-dimensional nature of the modelling, sediment reworked in an east–west direction by cross-platform currents, particularly in the central facies belt in the Pangkajene area, could not be modelled. The program is capable of modelling two phases of extension and, as evidenced by the redeposited facies derived from the northern margin of the Tonasa Platform, the two main phases of faulting occurred in the late Eocene to earliest Oligocene and early to middle Miocene. However, it is not possible to vary extension rates and amounts in a step-like manner within these two main phases of extension, or to add any additional minor phases of faulting and block rotation. Therefore, modelling multiple phases of progradation on the southern ramp-type margin, perhaps related to minor periods of tectonic quiescence, such as during the late Eocene, is not possible. However, the model should be able to represent the observed progradation of Oligocene deposits on the southern ramp-type margin during a period of relative tectonic quiescence. Pre-existing basement topography, which may have influenced sedimentation in the early middle Eocene, is not possible to show on the models. For this reason, the modelling was started in the late Eocene and run through to the middle Miocene, a total of 23 Myr.

Computer modelling results

A large number of model runs were undertaken, using different variables, and the best fit results with the input parameters are shown in Fig. 11. The accommodation space and gross sedimentary geometries generated during different time periods, including progradation on the southern ramp-type margin during the Oligocene, closely resemble those observed on the Tonasa Carbonate Platform. A number of unexpected implications for the development of the platform emerged from the computer modelling. First, a unique set of parameters was identified, which produced a model most closely resembling the development of the Tonasa Carbonate Platform. Secondly, it is only possible to produce the laterally variable available accommodation space for the platform using extremely low stretching factors (total beta of 1.012) and low rates of regional subsidence (0.02 m kyr⁻¹). Given the backarc setting of South Sulawesi for the Paleogene, the low rates of regional subsidence seem surprising and can best be explained by the Tonasa Carbonate Platform developing on a fault-bounded high, adjacent to the volcanic arc on the margins of the backarc basin (cf. Marsaglia, 1995). In the adjacent deep-water area of the south Makassar Straits, subsidence rates in the backarc basin were much higher and, for the early Paleogene, may have been as high as hundreds to a few thousand metres every million years (Situmorang, 1982). These rates are comparable with other backarc basins (Marsaglia, 1995). The low stretching factor (see below) relates to the orientation and location of the main northern faulted margin of the Tonasa Carbonate Platform, which was controlled by pre-existing structures and was not oriented perpendicular to the main extensional direction in the Makassar Straits.

The platform was also characterized by low rates of shallow-water sediment accumulation of around 0.2–0.3 m kyr⁻¹ (not allowing for compaction). This accounts for the volume of sediment within the Tonasa Carbonate Platform in the 23 Myr time interval. Higher production rates mean that the available accommodation space would have been overfilled. Even taking into account the possible effects of compaction or lateral east–west transport of shallow-water sediments, these accumulation rates are an order of magnitude lower than modern warm-water reefal production (1–4 m kyr⁻¹; Jones & Desrochers, 1992). However, these rates are comparable with production rates in modern tropical backreef and lagoonal areas (0.01–0.4 m kyr⁻¹; Bosence, 1989), where larger benthic foraminifera are common. These rates are also similar to, or an order of magnitude higher than, those found on modern and ancient ramps (Aurell et al., 1995).

COMPARISON WITH OTHER TERTIARY SE ASIAN CARBONATES

Carbonate sedimentation was extensive and varied in the tropical seas of SE Asia during the
Cenozoic (Fulthorpe & Schlanger, 1989; Wilson & Rosen, 1998). Eocene/Oligocene carbonate successions are dominated by larger benthic foraminifera or other calcite bioclasts, and tend to form isolated platforms, shelves or local shoals (Adams, 1965; Kohar, 1985; Siemers et al., 1992; Cucci & Clark, 1993). Corals and other aragonitic bioclasts are generally rare in these Paleogene carbonates, and the suggested reasons for this are a combination of biogeographic and ecological factors (Wilson & Rosen, 1998). In comparison, an aragonitic fauna is abundant in SE Asian Neogene carbonates, although larger benthic foraminifera and coralline algae are also common. Isolated platforms, shelves and particularly reefal buildups developed extensively during the Neogene (Wilson & Rosen, 1998).

SE Asia was an extremely active tectonic area throughout the Cenozoic, and carbonates formed in a variety of tectonic settings. These include foreland basins (Pigram et al., 1982; Wilson et al., 1993), forearc settings (Rose, 1983), island arcs (Fulthorpe & Schlanger, 1989) and backarc basins (Kohar, 1985; Tyrrel et al., 1986; Park et al., 1995). Outcrop, seismic and borehole data indicate that tectonic subsidence, faulting and earlier structures often strongly influenced the location and development of many of these carbonates, similar to the Tonasa Carbonate Platform (Fig. 12; Wilson & Bosence, 1996; Ascaria, 1997; Mayall et al., 1997). Carbonate platforms may develop with tilt-block morphologies, such as the central part of the Tonasa Carbonate Platform (Fig. 7), the Peutu Formation of Sumatra (Collins et al., 1996) and the Liuhua platform of the South China Sea (Fig. 12; Erlich et al., 1990, 1993). Horst-block platforms, as in the Western Divide area of the Tonasa Formation (Fig. 9), developed in the Luconia shoals (Epting, 1980) and the South China Sea (Fig. 12; Mayall et al., 1997). In some examples, faults cut the carbonate sequence and were syndepositional. In other areas, such as the Luconia shoals (Epting, 1980) or the northern margin of the Berai Limestone (Saller et al., 1993), carbonate production developed on antecedent fault-bounded highs, and it is not clear

---

**Fig. 12.** Seismic section through examples of tilt-block (upper) and horst-block (lower) carbonate platforms from SE Asia. The upper example is the Miocene Liuhua Carbonate Platform (from Erlich et al., 1993) in the South China Sea, showing similar morphology to that inferred for a north–south section through the Tonasa Carbonate Platform. The lower example is one of a number of horst-block platforms from the South China Sea (from Mayall et al., 1997).
whether the faults break through the platform successions. The margins of these platforms vary from faulted escarpments through reef-rimmed margins to ramp-type margins (commonly developed on the hangingwall of tilt-block platforms), although the morphologies of the platform margins may change through time.

Where it is possible to date the periods of faulting affecting carbonates, studied at outcrop or in the subsurface, these are often contemporaneous with regional plate tectonic events, as in the Tonasa Platform (Wilson & Bosence, 1996). An example of a subsurface carbonate complex with a similar history to the Tonasa Carbonate Platform is the Gunung Putih limestone described from the East Java Sea (Cucci & Clark, 1993). These late Eocene to Miocene carbonates were deposited on a broad tilt-block platform over a thin siliciclastic sequence, which was deposited on a bevelled Cretaceous–Tertiary platform. Oligocene subsidence associated with local tectonism resulted in partial drowning and a reduction in the area of shallow-water carbonate production. In the late Oligocene, a relative sea-level fall, produced primarily by tectonic uplift, resulted in partial erosion of the underlying Oligocene and Eocene deposits. During the early to middle Miocene, the Gunung Putih carbonate complex was again affected by subsidence, this time related to broad regional tectonism and folding (Cucci & Clark, 1993). In terms of facies distribution, morphology and its strong tectonic influence, the Tonasa Carbonate Platform provides a good analogue for Cenozoic SE Asian carbonates, particularly Paleogene examples, which comprise potential reservoirs in the subsurface.

COMPARISON WITH OTHER SYNTECTONIC PLATFORMS

Setting of syntectonic platforms

In extensional rift basins that become marine, syntectonic platforms commonly form on pre-existing faulted footwall highs (Leeder & Gawthorpe, 1987). Field examples of tilt-block platforms have been described from the Miocene Gulf of Suez (Burchette, 1988; Bosence et al., 1998; Cross et al., 1998), the Tertiary of Indonesia (van de Weerd & Armin, 1992), the Carboniferous of Ireland (Nolan, 1989; Pickard et al., 1992, 1994) and the Triassic of Italy (Martini et al., 1986). There are numerous examples of platforms that developed on pre-existing highs associated with block faulting (Epting, 1980; Williams et al., 1989; Collins et al., 1996; Masse et al., 1997). Some of these were syntectonic, such as during the Miocene in Indonesia (Mayall et al., 1997), the Carboniferous in northern England (Gawthorpe, 1986, 1987; Grayson & Oldham, 1987; Ebden et al., 1990) and Wales (Ramsay, 1989), the Mesozoic–Tertiary in Turkey (Robertson, 1993) and the Triassic–Jurassic in Italy (Cozzola & Gandin, 1990) and France (Elmi, 1990). Similar examples to the Tonasa Carbonate Platform, where pre-existing extensive carbonate platform successions have been segmented by extensional faulting and subsequent syntectonic carbonate deposition include the Carboniferous of northern England (Gutteridge, 1987, 1989), the Silurian of Greenland (Hurst & Surlyk, 1984), the Cretaceous of Spain (Rosales et al., 1994), the Jurassic of Italy (Bice & Stewart, 1990; Santantonio, 1994) and the Cambrian of Sardinia (Cozzola & Gandin, 1990).

Extensional faulting and platform geometries

During extensional basin formation, faults at right angles to the extension direction generally form with a perpendicular spacing of up to a few tens of kilometres. Tilt-block carbonate platforms with limited areal extent commonly develop on these footwall highs (Burchette, 1988; Pickard et al., 1994; Bosence et al., 1998; Cross et al., 1998). Detailed studies of these well-exposed, small-scale, tilt-block platforms have allowed the recognition of repeated footwall uplift, footwall to hangingwall stratal thickening and progressive upsequence decrease in dip. Identification of lateral changes in shallow-water facies related to transfer zones, and the differentiation of sequences deposited during block rotation or relative sea-level change has also been possible (Burchette, 1988; Rosales et al., 1994; Bosence et al., 1998; Cross et al., 1998). The formation of the Makassar Straits was initiated during the Paleogene in a backarc setting, to the west of a volcanic arc related to oblique westward subduction (van de Weerd & Armin, 1992; Hall, 1996). Although there may have been considerable transtensional faulting (Bransden & Matthews, 1992), the main extensional direction, assuming no rotation, was east–west. A number of north- to south-trending faults segmented the Tonasa Formation in the Western Divide area and resulted in the formation of small-scale, syntectonic, tilt-block and horst-block platforms (Fig. 9). However, poor exposures and difficulties of correlation do not allow
detailed differentiation of sequences within individual fault-block successions in this area.

In comparison with the examples above, the main Tonasa Carbonate Platform was a much larger scale syntectonic platform (Fig. 7), where thick shallow successions accumulated, and the main northern platform-bounding faults trended NW–SE oblique to the extension direction. Within the region, NW- to SE-trending lineaments, such as the Adang and Sankulirang Fault Zones, strongly controlled Cenozoic sedimentation patterns and were probably the result of heterogeneities in underlying pre-Tertiary basement and reactivation of pre-existing regional structures. Large-scale platforms with thick carbonate successions, such as the Paternoster and Mangkalihat Platforms, like the Tonasa Platform, only developed on footwall highs because of overall regional subsidence. Major normal-fault zones, extending over hundreds of kilometres, are broken into smaller faults with lengths up to a few tens of kilometres separated by accommodation zones (Roberts & Jackson, 1991; Morley, 1995). Cross et al. (1998) documented detailed facies variations and shallow-marine carbonate sequence evolution in a relay ramp zone separating two normal faults. The faults bounding the northern margin of the tilt-block Tonasa Platform are also inferred to have been separated by a relay ramp (Fig. 7). However, sedimentation in this area occurred in a deep-marine setting, influencing the distribution of reworked carbonates derived from footwall highs (Wilson & Bosence, 1996).

Terrigenous supply and nutrients

In many synrift carbonate platforms, particularly during the transition from terrestrial to marine sedimentation, clastics derived from nearby uplifted eroding areas may strongly influence the lateral extent and facies distribution of carbonates preferentially developed on footwall highs (Scott & Govean, 1985; Leeder & Gawthorpe, 1987; Bosence, 1998; Cross et al., 1998; Purser et al., 1998). In these settings, nutrient influx may also influence carbonate facies development and, in arid climates, evaporites can form in adjacent restricted hangingwall basins (Cocozza & Gandin, 1990; Cross et al., 1998; Purser et al., 1998). In comparison, the Tonasa Carbonate Platform was effectively an isolated platform and, although volcanism limited the eastward lateral extent of the platform, clastic and nutrient influx had little effect on carbonate development. This lack of clastic influx is common to other large-scale platforms that have been later segmented by faulting (Hurst & Suryk, 1984; Rosales et al., 1994; Santantonio, 1994). SE Asia is a tropical area with high annual rainfall, and flooding occurs on a regular basis. In addition, the seaways between islands are areas of intermixing of Pacific and Indian Oceanic waters, where there is constant current activity and, as a consequence, evaporites are rare.

Platform margins

The large-scale, syntectonic, tilt-block Tonasa Platform is similar to other carbonates developed on tilted fault blocks, in that the faulted margin is characterized by escarpments and a ramp-type margin developed on the dip slope (Martini et al., 1986; Burchette, 1988; Rosales et al., 1994; Masse et al., 1997; Cross et al., 1998). Corals are rare in the shallow-water deposits of the Tonasa Formation and the material reworked into hangingwall depocentres, and there is no evidence for reefal frameworks developed along the escarpment margin. This is at variance with other Cenozoic tilt-block platforms, where reef-rimmed margins often develop. The lack of in situ framework growth would have affected the potential for reworking and stability of the platform margin. It is inferred that the location of barriers and cross-platform currents influenced the development of facies belts on the platform.

Depositional sequences

Depositional sequences on well-exposed, small-scale, tilt-block platforms show tilting of beds (up to 4°), recognizable thickening down the hangingwall dip slope and hangingwall sequences bounded by unconformities. These have been related to deposition during faulting and rotation of the fault block (Leeder & Gawthorpe, 1987; Bosence et al., 1998; Cross et al., 1998). In contrast, parallel-sided depositional sequences, which pass over the footwall area, relate to regional relative sea-level variations (Cross et al., 1998). Rosales et al. (1994) described carbonate depositional sequences on the dip slope of a tilt-block platform, which show pronounced onlap at their base and in which the transgressive and deeper deposits of the hangingwall cannot be correlated with karstification surfaces on the footwall high. These have been interpreted as passive fill of the wedge-shaped accommodation space during a regional relative sea-level rise
(cf. Bosence, 1998). Post-depositional faulting, poor exposure of platform margin deposits, dense vegetation and the difficulties of accurate correlation between sections make recognition of such sequences on the Tonasa Platform impossible. However, the Tonasa Platform is unusual in that both platform-top and basinal deposits are exposed, and dating of a number of phases of syndepositional faulting is possible.

**Dipslope progradation**

Downslope progradation of dipslope facies (Blen-dinger, 1986; Pickard et al., 1992) and dominantly aggradational facies geometries on the crest of the footwall block have been observed in other ancient tilt-block platforms (Hurst & Surlyk, 1984; Burchette, 1988). In the case of the Tonasa Platform, the position of the inferred ‘barrier’ between the platform-top deposits and the southern ramp-type margin is not known because volcanioclastic overlie the carbonate succession between the Pangkajene and Jeneponto areas. The minimum southward progradation of the southern ramp-type margin was a few kilometres, based on the spacing between onshore and subsurface offshore contemporaneous deposits. Progradation of the ramp deposits may have occurred during periods of non-rotation of the fault block, as shown by computer modelling.

**CONCLUSIONS**

This study allows the construction of a facies model for a Cenozoic foraminifera-dominated tropical, fault-block carbonate platform. This provides a meaningful analogue for other similar SE Asian carbonate platforms, which form potential hydrocarbon reservoirs. Results from this research also have implications for the study of syntectonic carbonates, controls on carbonate sedimentation, carbonate development in backarc areas and SE Asian tectonics.

The Eocene to middle Miocene Tonasa Formation developed as a complex, large-scale syntectonic platform, which formed as part of a transgressive sequence in a backarc setting. Initial carbonate sedimentation was diachronous, but spread to form a more extensive shallow-water carbonate platform dominated by larger benthic foraminifera by the late Eocene. Fault segmentation of this broad carbonate platform occurred during the later part of the late Eocene, resulting in complex fault-block platforms, separated by graben or half-graben. Subaerial exposure or shallow-water carbonate sedimentation occurred on horst blocks, while deeper marine marls and coarse conglomerates resedimented from faulted highs were deposited into adjacent graben during the late Eocene to middle Miocene. Platform-top areas were dominantly aggradational. Low-relief slopes, particularly on the dip slopes of hanging-wall blocks, were characterized by ramp development. Steep escarpment margins were formed by periodically active faults. A combination of tectonic subsidence, faulting, pre-existing structures, oceanography, climate and dominant carbonate-producing organisms were the main factors influencing evolution, morphology, facies distributions and depositional sequences on this carbonate platform.

In terms of dominant biota, facies distribution, morphology and the strong tectonic influence, the Tonasa Carbonate Platform provides a good analogue for other more poorly exposed Paleogene SE Asian carbonate platforms. The locations of faults affecting the siting and development of these platforms were related to pre-existing regional structures, inhomogeneities in underlying basement blocks and extension direction. The syndepositional faulting affecting many of the carbonate successions was often contemporaneous with regional tectonic events.

The Tonasa Carbonate Platform is unusual among syntectonic platforms in that initial widespread platform sedimentation was segmented by faults, and both tilt- and horst-block platforms developed on a variety of scales. The main tilt-block platform had a segmented, faulted, northern escarpment margin and a southern ramp-type margin, similar to other syntectonic platforms. It was not possible to apply a sequence stratigraphic approach to studying this platform, as with many other syntectonic platforms. Unusually, however, both platform-top and basinal lithologies are exposed, and it is possible to date phases of faulting on the platform margin. In addition, extensive carbonate sedimentation occurred continuously over a long time period (>30 Ma), and thick platform-top (>600 m) and slope (>1000 m) deposits developed. This was a result of the development of an isolated platform at the margins of a backarc basin undergoing regional subsidence.

Computer modelling of the tilt-block platform shows that it is possible to duplicate the accommodation space and sedimentary geometries observed on the Tonasa Platform. This was achieved using a unique set of parameters and by

invoking regional subsidence and block faulting, without the need for eustatic variation. Modelling also shows that regional subsidence and extension oblique to the main stretching direction were low on the margins of the backarc basin. Shallow-water accumulation rates for this foraminiferadominated carbonate platform were an order of magnitude lower than those for modern tropical platforms, characterized by corals and other framework-building organisms or ooids.

ACKNOWLEDGEMENTS

We gratefully acknowledge BP Exploration, UK, for their generous financial support during the course of the senior author’s PhD study, of which much of this work forms a part. The SE Asia Research Group, University of London, especially Dr Tony Barber, Professor Robert Hall and Diane Cameron, are thanked for their technical and administrative support. In Indonesia, GRDC, Bandung, Kanwil, South Sulawesi, BP offices in Jakarta and Ujung Pandang, LIPI and many people in Sulawesi all provided technical and practical support. Dr Ted Finch and Professor Fred Banner, both at University College London, and Dr Toine Wonders, Consultant, UK, are thanked for their detailed biostratigraphic work. Constructive comments by Brian Jones, Christian Betzler and the editor, Ian Jarvis, helped to improve this manuscript.

REFERENCES


Syntectonic platform carbonate development 419


Manuscript received 8 April 1998; revision accepted 13 August 1999.