IPA96 - 1.1 - 154

PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Twenty-Fifth Silver Anniversary Convention, October 1996

EVOLUTION AND HYDROCARBON POTENTIAL OF THE TERTIARY TONASA LIMESTONE FORMATION, SULAWESI, INDONESIA

Moyra E.J. Wilson*

ABSTRACT

Many carbonate successions in SE Asia are excellently placed with respect to source and seal lithologies and often form hydrocarbon reservoirs. This paper outlines the depositional history of the Eocene to middle Miocene Tonasa Limestone Formation of South Sulawesi and evaluates the implications for hydrocarbon exploration in the region.

The Tonasa Limestone Formation was deposited initially as part of a transgressive sequence, in the midst of an exceedingly complex tectonic area. Detailed facies mapping and logging reveal that by late Eocene times shallow-water carbonates were being deposited over much of South Sulawesi forming a widespread (100 km length) platform area, known as the Tonasa Carbonate Platform. Although shallow-water sedimentation was continuous until the middle Miocene on some areas of the platform, active normal faulting resulted in basinal graben formation and sub-aerial exposure in other areas.

Platform top lithologies are dominated by large benthic foraminifera and consist of wackestones, packstones and grainstones. Platform top facies belts trend E-W and were relatively static through time, indicating subsidence and aggradation of the platform top. Tertiary exposure of shallow-water facies occurred only in areas close to those affected by block faulting. In fault bounded graben areas, basinal marls are interbedded with thick sequences of coarse, immature redeposited carbonate facies, which contain clasts from the underlying formations. These redeposited facies are inferred to have been derived from the footwall areas of syn-depositional faults.

The lack of abundant aragonitic bioclasts, together with only localized subaerial exposure result in little porosity and permeability development in platform top lithologies. In comparison, redeposited facies derived from block faulted areas are both porous and permeable, and comprise the lithologies most likely to form hydrocarbon reservoirs within this formation. This study has implications for hydrocarbon exploration in other Tertiary carbonate successions dominated by foraminifera, which occur widely throughout Southeast Asia.

* University of London

INTRODUCTION

Almost half of Indonesia's (Park et al., 1995), and indeed the world's (Dickey, 1986) hydrocarbon production comes from carbonate reservoirs. Much of SE Asia remained in near tropical latitudes throughout the Tertiary, and shallow-water areas away from clastic input often developed thick carbonate successions. Actual and potential hydrocarbon bearing carbonates occur in many locations in SE Asia, excellently placed with respect to source and seal lithologies, and very definitely form worthwhile exploration targets. However, carbonate reservoirs are notoriously unpredictable (Park et al., 1995). Only through a knowledge of the processes of carbonate sedimentation, the development and growth of carbonate platforms, and the subsequent diagenesis of carbonates lithologies can we better understand the inheterogeneity of carbonate reservoirs. This paper reviews the evolution of the Eocene to middle Miocene Tonasa Carbonate Platform of South Sulawesi and evaluates the implications for hydrocarbon exploration in the region.

TECTONOSTRATIGRAPHIC SETTING OF SOUTH SULAWESI

Western Sulawesi has been located at the eastern margin of Sundaland, the relatively stable cratonic area of Southeast Asia, throughout the Cenozoic. The geological history of this area is inextricably linked to the accretion of microcontinental and oceanic material onto the eastern margin of Sundaland and to the resultant development of volcanic arcs. Sulawesi forms distinct north-south trending tectonic provinces (Sukamto, 1975). These comprise from west to east the Western Sulawesi Tectono-Plutonic Arc, the Central Sulawesi Metamorphic Belt, the East Sulawesi Ophiolite and the microcontinental blocks of Banggai-Sula and Buton-Tukang Besi (Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981; Parkinson, 1991; Wilson, 1996). The Western Sulawesi Plutono-Volcanic Arc, which includes outcrops of the Tonasa Limestone Formation, is composed of thick Tertiary sedimentary and volcanic sequences overlying pre-Tertiary basement complexes (Sukamto 1975; van Leeuwen 1981). The Tertiary stratigraphy of western Sulawesi is comparable with many of the Tertiary basins in neighbouring east Kalimantan and the East Java Sea, and the whole area is thought to have comprised a widespread basinal area (van de Weerd and Armin 1992).

South Sulawesi (Figure 1), located on the eastern margin of Eurasia, has an almost complete stratigraphic sequence spanning the late Cretaceous to the present day, with carbonate deposits spanning much of the Tertiary (Figure 2, Sukamto 1975; Hamilton 1979; van Leeuwen 1981). During the late Cretaceous, deep marine clastics and shales of the Balangbaru and laterally equivalent (van Leeuwen, 1981) Marada Formations were deposited over tectonically stacked metamorphic, ultrabasic and sedimentary basement lithologies in western South Sulawesi (Figure 1). 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 which pass transgressively upwards into carbonates of the Tonasa Limestone Formation were deposited over the western part of South Sulawesi. During the deposition of these sedimentary units, the lithologies in eastern South Sulawesi were dominated by volcaniclastic and igneous lithologies of the Salo Kalupang and Kalamiseng Formations (Sukamto 1982; Yuwono et al., 1987). The Eocene/Oligocene lithologies are thought to be the products of a calcalkaline volcanic arc, whilst the Kalamiseng Formation may be an ophiolitic sequence, accreted during the Oligo/Miocene (Yuwono et al., 1987). This suggests that the Tonasa Limestone Formation was deposited initially as part of a transgressive sequence in a back-arc setting. The Tonasa Limestone Formation is overlain by volcaniclastic deposits of the Camba Formation, which were derived from a volcanic arc which developed in western Sulawesi in the middle to late Miocene (Sukamto 1982; Yuwono et al., 1987). This volcanic activity may be related to lithospheric thickening resulting from continent-continent collision onto eastern Sulawesi (Coffield et al., 1993; Bergman et al., 1996).

THE TONASA LIMESTONE FORMATION

Outcrops of the Tonasa Limestone Formation occur only to the south of a NW-SE trending depression which passes through Lake Tempe and mainly to the west of the Walanae Depression (Figures 1 and 2). Detailed facies mapping and logging throughout the area of outcrop of the Tonasa Limestone Formation, and subsequent petrographic analysis of carbonate lithologies, have revealed that during the early/middle Eocene to middle Miocene a widespread area of shallow-water carbonate production, known as the Tonasa Carbonate Platform, developed in South Sulawesi (Wilson, 1995). Large benthic foraminifera dominate lithologies of this platform, which were deposited within the photic zone. Other bioclasts include coralline algae, echinoid fragments, small benthic foraminifera and small amounts of coral debris. The carbonates of the Eocene to middle Miocene Tonasa Limestone Formation include over a kilometre of shallow-water lithologies overlain by basinal deposits presently located to the north and south of the main platform area (Wilson, 1995). The Tonasa Carbonate Platform had a north/south extent of about 100 km and from late Eocene the platform was bounded by a steep segmented northern platform margin and a gently dipping ramp type southern margin (Wilson, 1995). Areas of more complex block faulting lay to the east and west of the main area of the Tonasa Carbonate Platform (Wilson, 1995). Detailed analysis of platform and surrounding basinal deposits reveal that the Tonasa Carbonate Platform was affected by a number of phases of syn-depositional tectonic activity (van Leeuwen, 1981; Wilson, 1995; Wilson and Bosence, 1996). This paper summaries the evolution of the Tonasa Carbonate Platform through the Tertiary and evaluates the hydrocarbon potential of the Tonasa Limestone Formation and the implications this study has for hydrocarbon exploration in the region. It is beyond the scope of this paper to give all the detailed facies descriptions and interpretations for different parts of the carbonate platform, leading to the evolutionary model outlined below. For this information the reader is referred to a series of publications (Wilson, 1995; Wilson and Bosence, 1996; Wilson and Bosence, in press).

The changes in depositional environment, nature of the margins and lateral extent of the Tonasa Carbonate Platform are summarized below. Figure 3 shows plan views of the inferred palaeogeography of South Sulawesi during the deposition of the Tonasa Limestone Formation. The depositional history of the Tonasa Carbonate Platform and surrounding basinal areas are shown on Figure 4. Figure 5 illustrates a reconstruction of the western half of the Tonasa Carbonate Platform during the late Eocene or Oligocene.

EVOLUTION OF THE TONASA CARBONATE PLATFORM

Early/Middle Eocene

Marginal-marine clastics of the Malawa Formation and volcaniclastics of the Langi Volcanics pass transgressively upwards into shallow-marine carbonates of the Tonasa Limestone Formation in the western and eastern parts of South Sulawesi. Although there was some interdigitation of the Tonasa Limestone Formation and underlying formations, the transition to carbonate sedimentation appears to have been rapid. Only the lowermost few metres of the carbonate succession contain siliciclastic grains reworked from the underlying formations.

The only area onshore Sulawesi with exposed latest early or early middle Eocene carbonate sediments is the northerly Barru Area (Wilson, 1995). Palynological data from the Tonasa-I Quarry suggests that the Malawa Formation in the Pangkajene Area is middle to late Eocene in age (Crotty and Engelhardt, 1993). Although the base of the Tonasa Limestone Formation is not exposed in the southerly Jeneponto Area (Figure 1), the oldest marls exposed in this area have a middle to late Eocene age (NP17-20). Borehole data to the south of Ujung Pandang and offshore southwest Sulawesi also suggest that carbonate sedimentation occurred in the early/middle Eocene.

Thus the beginning of carbonate sedimentation in South Sulawesi was diachronous. The northern Barru and southerly Jeneponto areas are inferred to have been the sites of earliest carbonate sedimentation during the early to middle Eocene. Marginal marine to marine sediments of the Malawa Formation or volcaniclastics of the Langi Formation were deposited in the central parts of western South Sulawesi during this period.

In the northerly Barru Area, a variety of wackestone, packstone and grainstone lithologies suggest that early carbonate sedimentation is inferred to have occurred in a range of shallow-marine environments (Wilson, 1995). The presence of abundant *Potamididae* gastropods and rare crystal pseudomorphs after gypsum or anhydrite in some initial carbonate deposits is taken as evidence for localized restricted conditions (Wilson, 1995). However, the occurrence of large perforate foraminifera and corals in many other initial carbonate sediments suggests stenohaline conditions (Wilson, 1995). The occurrence of East-West trending grainstone and packstone units containing abundant robust, and often fragmented, large benthic foraminifera, separated by lower energy wackestones and packestones, suggests the development of moderate to high energy shoals, with lower energy intervening areas (Wilson, 1995).

The oldest sediments exposed in the southerly Jeneponto Area are well-bedded bioclastic packstones interpreted as middle to outer ramp deposits with an open ocean influence (Wilson, 1995; Wilson and Bosence, in press). It is not known if these deposits overlie shallow-marine or marginal marine deposits.

Late Eocene

During the late Eocene, carbonate sedimentation spread to the Pangkajene, Segeri and Western Divide Mountain Areas of South Sulawesi (Figure 3; Wilson, 1995). Although initial carbonate sediments in these areas all occur within the same biostratigraphic zone

(Tb), dating is not precise enough to ascertain whether the transition to carbonate sedimentation was synchronous. Some interdigitation with underlying formations in these areas suggests a diachronous change.

Late Eocene carbonates are exposed in a small outcrop in the north, in more extensive areas in the central parts of the Pangkajene Area, and in most outcrops located in the Western Divide Mountain Area. These lithologies consist of large benthic foraminifera grainstones, packstones and wackestones and suggest that initial carbonate sediments in these areas were deposited in a range of moderate to high energy environments in shallow to moderate water depths in the photic zone (Wilson, 1995). A broad platform area composed of shoals, channels and intervening lower energy regions is envisaged for these areas (Wilson, 1995). The single occurrence of late Eocene carbonates to the east of the present day Walanae Depression indicate that shallow-water deposits of the Tonasa Carbonate Platform might have extended laterally across this area. Palaeocurrent data from the central part of the Pangkajene Area indicates that the dominant transport direction was towards the east (Wilson and Bosence, in press).

In the Pangkajene Area, localized evidence for possible late Eocene subaerial exposure occurs in just a few sections (Wilson, 1995). In the area of the Western Divide Mountains, late Eocene deposits in sections close to Bantimala, Malawa, Ujunglamuru and Maborongnge have been karstified (Figure 4). Subaerial exposure and tilting of carbonate lithologies in these locations occurred during or after the late Eocene and before the deposition of the Camba Formation in the middle Miocene (Wilson, 1995). In complete sequences through the Tonasa Limestone Formation close to the villages of Bua and Biru, late Eocene carbonate facies show no evidence for karstification and are inferred to deepen up-section (Wilson, 1995).

In the northerly Barru Area, during the early part of the late Eocene, carbonate sedimentation continued as a series of shoals, probably trending East-West, with lower energy intervening as described above. Carbonate facies in the Rala section deepen upwards and the greatest thickness of late Eocene deposits in the Barru Area is present in this locality. Other late Eocene deposits, such as those in the Doi-doi and Bangabangae sections, are thinner and show no corresponding deepening upward trend (Wilson, 1995). The deposition of bioclastic packstone and grainstones, many containing planktonic foraminifera, marks a change in the late Eocene depositional environment in the Barru Area. The facies distribution of these packstones and grainstones suggests that moderate to high energy outer shelf conditions in the Doi-doi area passed northwards into slope deposits with an open ocean influence in the Rala area (Wilson, 1995). These slope deposits probably delineate the northern margin of the Tonasa Carbonate Platform (Figure 3, Wilson, 1995).

In the northern part of the Barru Area, during the later part of the late Eocene, bioclastic packstones and grainstones pass sharply upward into thick sequences of basinal marls interbedded with coarse redeposited carbonate facies indicating rapid deepening (Wilson and Bosence, 1996). These redeposited facies contain clasts of the underlying formations in South Sulawesi and are inferred to have been derived from major normal faults bordering the Tonasa Carbonate Platform (Figure 3; Wilson and Bosence, 1996). The preferred configuration of the northern margin of the Tonasa Carbonate Platforms during the later part of the late Eocene is of an east-dipping relay ramp between two main NW-SE trending, syn-depositional normal faults which bound the northern margins of the Bantimala and Barru Blocks (Figures 3 and 4; Wilson and Bosence, 1996). The localized occurrence of siliciclastic grains just prior to rapid deepening and deposition of marls in the northern part of the Barru Area may be related to exposure of siliciclastic lithologies during the early stages of faulting (Wilson, 1995). The northern margin of the Tonasa Carbonate Platform was marked by a faulted escarpment margin, which was periodically active from the later part of the late Eocene through to the middle Miocene (Wilson and Bosence, 1996).

In the Segeri Area, late Eocene deposits comprise a thin sequence of shallow-marine packstones and grainstones, containing abundant large benthic foraminifera (Wilson, 1995). The lowermost beds within these deposits contain angular siliciclastic grains, suggesting reworking of older formations (Wilson, 1995). During the latest Eocene, a rapid change occurred in the Segeri Area, with the initiation of the deposition of marls interbedded with redeposited carbonate facies. An abrupt facies change, contemporaneous deeper-water sedimentation and localized subaerial exposure, and the textural immaturity of redeposited facies all suggest active block faulting in this area at this time (Wilson, 1995).

The background sedimentation in the southerly Jeneponto Area is of basinal marls (Wilson and Bosence, in press). However, unlike the Barru and Segeri Areas there is no evidence for major shedding of syntectonic carbonate sediments into this basinal area (Wilson, 1995). In contrast, mid to outer ramp deposits of the southern margin of the Tonasa Carbonate Platform prograded southwards into basinal deposits at least twice during the late Eocene (Wilson and Bosence, in press). Lithic grains in late Eocene packstones in the Jeneponto Area indicate reworking of the underlying formations and/or a volcaniclastic input (Wilson, 1995). Easterly directed palaeocurrent data on the Tonasa Carbonate Platform suggest a westerly source for these siliciclastics. The Makassar Straits are thought to have been an area of active faulting during the late Eocene (Bransden and Matthews, 1992).

Oligocene

Predominantly aggradational sequences of Oligocene shallow-water foraminiferal wackestone, packstones and grainstones, which almost entirely lack lithic grains, are exposed throughout much of the Pangkajene Area (Wilson and Bosence, in press). Open oceanic conditions are inferred to have existed to the southwest of the Pangkajene Area due to the occurrence of abundant planktonic foraminifera in the upper part of one section (Wilson and Bosence, in press). The distribution of mudstone and wackestone facies indicates that the northern and southern parts of the Pangkajene Area were regions of low to moderate energy with shallow to moderate depths in the photic zone (Figure 4). Small coral patch reefs are thought to have developed only in the southern part of the Pangkajene Area (Wilson and Bosence, in press). In contrast, the predominance of grainstones and packstones in the central part of the Pangkajene Area suggests that moderate to high energy conditions prevailed in this area (Wilson and Bosence, in press). These facts, together with mostly east directed palaeocurrents (Wilson, 1995), suggest that the northern and southern parts of the Pangkajene Area were protected and sheltered by some form of barrier (Figure 4; Wilson, 1995). Localized evidence for Oligocene intertidal sedimentation and possible subaerial exposure and karstification occur only in the northern part of the Pangkajene Area (Wilson and Bosence, in press).

In the area of the present day Western Divide Mountains, Oligocene deposits are exposed only along the eastern flank of the Bantimala Block and in the Biru area (Wilson, 1995; van Leeuwen, 1981). In these localities, shallow-water deposits of probably early Oligocene age were subaerially exposed and eroded later in the Oligocene. In the Biru area, packstones and grainstones overlying a brecciated horizon, thought to indicate evidence for exposure, contain planktonic foraminifera indicating an open oceanic influence during the late Oligocene/early Miocene (van Leeuwen, 1981; Wilson, 1995).

During the Oligocene, the Tonasa Carbonate Platform is inferred to have been bordered in the Barru Area by an escarpment margin, with deeper basinal marl sedimentation occurring to the north. Shedding of coarse immature redeposited facies from this margin suggests a period of active normal faulting during the early/late Oligocene (Wilson and 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. However, it is not clear whether the inferred late Eocene basin bounding faults in this area were still active during the Oligocene (Wilson, 1995).

Well-bedded Oligocene packstones in the Jeneponto Area, suggest that mid to outer ramp deposits of the southern margin of the Tonasa Carbonate Platform prograded southwards into basinal deposits (Wilson and Bosence, in press).

Miocene

Miocene deposits in the Pangkajene Area were seen only in the uppermost parts of a southerly and southwesterly section (Wilson, 1995). In the southwesterly section abundant planktonic foraminifera in some beds indicate an open oceanic influence. In comparison, the large benthic foraminifera packstones and grainstones in the southerly section indicate shallow-water, moderate energy shelf conditions (Wilson and Bosence, in press). In this section the contact with the overlying Camba Formation is a conformable one. The lower member of the Camba Formation at this locality is composed of marginal-marine to terrestrial coals and palaeosols interbedded with volcaniclastic siltstones and sandstones (Wilson, 1995).

The variety of early/middle Miocene carbonate lithologies in the Western Divide Mountains Area, such as large benthic foraminifera packstones, marls and redeposited carbonate facies suggests a range of shallow to deeper-water environments (Wilson, 1995). In the deeper water areas, marls occur interbedded with thick beds of coarse, texturally immature clast-supported breccias suggesting tectonic instability and block-faulting (Wilson, 1995). In other areas, the Camba Formation overlies karstified shallow-water wackestones and packstones of the Tonasa Limestone Formation with varying age ranges. Near Camba, karstification and tilting of Miocene shallow-water packstones occurred prior to the deposition of marginal-marine sediments of the lower Camba Formation. However, in other areas, thick marine successions of the lower Camba Formation conformably overlie unkarstified deposits of the Tonasa Limestone Formation. The Camba Formation is interpreted as having been deposited over an irregular surface with variable submarine and subaerial topography, thought to be the result of block-faulting (Wilson, 1995).

Active late Oligocene to early/middle Miocene faulting along the northern margin of the Tonasa Carbonate Platform is inferred from coarse clast-supported breccias, with bed thicknesses of up to 25 m, in the Barru Area (Wilson and Bosence, 1996). Both conformable and angular unconformable contacts with the overlying Camba Formation occur in this area (Wilson and Bosence, 1996). Although Miocene limestones are not exposed in the northern part of the Pangkajene Area, shallow-water carbonate production is inferred for this area due to the presence of Miocene shallow-water limestone clasts within redeposited facies in the Barru Area.

Miocene shallow and deeper-water areas occurred in close proximity to each other in the Segeri Area (Wilson, 1995). Coarse redeposited facies of Miocene age interbedded with basinal marls are rare in this locality. This suggests that Miocene basinal deposits are the result of passive infill and were probably not greatly affected by syn-depositional tectonic activity (Wilson, 1995). Prior to the deposition of the Camba Formation, the Miocene shallow-water carbonates close to Segeri were subaerially exposed, karstified and tilted (Wilson, 1995). Middle Miocene volcaniclastic deposits of the Camba Formation and older lithologies in the Segeri Area were folded, faulted and overthrust towards the southwest in a period of compression.

In the Jeneponto Area the background sedimentation during the early/middle Miocene is of basinal marls (Wilson and Bosence, in press). Interbedded with these marls are planktonic foraminifera wackestones which may be the distal deposits of redeposited carbonate facies (Wilson, 1995). If these deposits are distal redeposited facies, the southern Jeneponto Area was more unstable during the Miocene than the Oligocene and Eocene. Tilting of the carbonate sequence is inferred from the low angle unconformity between the Tonasa Limestone Formation and deep-marine shales and interbedded volcaniclastics of the lower member of the Camba Formation (Wilson, 1995).

HYDROCARBON EXPLORATION

Carbonate successions, widespread throughout Southeast Asia and having considerable potential as hydrocarbon reservoirs, were generally deposited in a range of tectonic settings (Fulthorpe and Schlanger, 1989) and had a variety of morphologies (Sun and Esteban, 1994). Miocene carbonate buildups identified from seismic reflection profiles, when drilled are often found to have good porosity and permeability and may yield hydrocarbons (Grainge and Davies, 1983; Mayall and Cox, 1988). Coral rich framestones or rudstones often form the best hydrocarbon reservoirs in Miocene deposits (McArthur and Helm, 1982; Grainge and Davies, 1983; Rose, 1983; Longman, 1985; Mayall and Cox, 1988). By comparison Eocene or Oligocene carbonate successions, such as the Tonasa Limestone Formation, are commonly found to be tight and are dominantly composed of large benthic foraminifera and other non aragonitic bioclasts (Adams, 1965; Kohar, 1985; Siemers et al., 1992; Cucci and Clark, 1993). Corals and other aragonitic bioclasts do occur in carbonates of this age, but are usually scarce, and to date only a few reports of moderate coral reefal faunas in carbonate successions of this age occur (Wilson et al., 1996).

The nature of carbonate deposition of the Tonasa

Limestone Formation and the evolution of the platform controlled its porosity and permeability development. The lack of abundant aragonitic bioclasts from corals or green algae, together with only localized subaerial exposure, result in little porosity and permeability development in shallow-water deposits of the Tonasa Limestone Formation. Primary porosity in high energy grainstone units, which occur in an East-West trending facies belt in the central part of the Pangkajene Area, has been occluded by equant sparry calcite, probably during burial under a thick volcaniclastic pile. However, it may be that in similar deposits, which have not been affected by adverse pore occluding diagenetic processes, primary porosity may be preserved in higher energy units. By comparison, redeposited carbonate facies of the Tonasa Limestone Formation derived from block faulted footwall areas may be both porous and permeable, indicated by circum-granular stylolites and some preserved primary intergranular porosity. Although concentrations of argillaceous material around clasts in some beds may lead to reduced permeability, redeposited facies, abutting impermeable basement and platform lithologies, are thought to form the most suitable hydrocarbon reservoir within the Tonasa Limestone Formation and indeed traces of hydrocarbons do occur. Overlying marine clays may form effective seals with underlying coal deposits providing a potential source (cf. Phillips, et al., 1991; Coffield, et al., 1993). This study suggests that redeposited carbonate facies may form effective hydrocarbon reservoirs in otherwise tight foraminiferal dominated carbonates. Fulthorpe and Schlanger (1989) recognized that in seismically active areas, carbonate megaturbidites could provide pathways for the migration of hydrocarbons, or act as reservoirs. Other factors which may affect porosity and permeability development in tight foraminiferal limestones include karstification, tectonic fracturing and the development of stylolites (Siemers, et al., 1992).

CONCLUSIONS

In summary, initial sedimentation of the Tonasa Limestone Formation was diachronous and began in the northern Barru and southern Jeneponto Areas during the early/middle Eocene. Carbonate sedimentation spread to all areas of exposure of the Tonasa Limestone Formation during the late Eocene. The late Eocene was a period of widespread foraminifera dominated platform carbonate sedimentation and is thought to have been the time when the Tonasa Carbonate Platform was at its greatest areal extent. Faulting and segmentation of this broad carbonate platform occurred in the Barru and Segeri Areas in the latest Eocene. During the Oligocene, shallow-water platform areas with localized subaerial exposure were present in the Pangkajene and Segeri Areas. At this time, deeper water areas were situated to the north, west and south of the main shallow-water carbonate platform. The southern margin of the Tonasa Carbonate is seen as a gently sloping ramp type margin, whilst the northern platform margin was a faulted escarpment margin with periodic tectonic activity. There was most likely active faulting along the northern margin of the Tonasa Carbonate Platform during the late Eocene and middle Oligocene. The early to middle Miocene saw widespread block-faulting, affecting most areas of the Tonasa Limestone Formation. Marginal-marine, marine and volcaniclastic sediments of the Camba Formation were deposited over an irregular surface with variable submarine and subaerial topography.

The Tonasa Limestone Formation is similar to many other carbonate successions in SE Asia in that it occurs initially as part of a transgressive sequence, overlying potential source deposits and is itself overlain by marine clays which may form effective seals. However, the lack of abundant aragonitic bioclasts, together with only localized subaerial exposure result in little porosity and permeability development of platform top lithologies of the Tonasa Limestone Formation. In comparison, redeposited facies derived from block faulted areas are both porous and permeable. These sometimes oil-stained facies, abutting impermeable basement and platform top lithologies, are the most likely carbonate reservoirs within the Tonasa Limestone Formation. This study has implications for hydrocarbon exploration in other Tertiary carbonate successions, which occur widely through SE Asia, and which are dominated by foraminifera and have undergone only localized sub-aerial exposure.

REFERENCES

Adam, C.G., 1965, The foraminifera and stratigraphy of the Melinau Limestone, Sarawak, and its importance in Tertiary correlation, Quarterly Journal of the Geological Society, London, 121, 283-338.

Bergman, S.C., Coffield, D.Q., Talbot, J.P. and Garrard, R.A., 1996, Tertiary Tectonic and magmatic evolution of western Sulawesi and the Makassar Strait: evidence for a Miocene continent-continent collision, In: Hall, R. and Blundell, D.J. (eds.), Tectonic evolution of SE Asia, Geological Society of London Special Publication, 106, 391-429.

Bransden, P.J.E. and Matthews, S.J., 1992, Structural and stratigraphic evolution of the east Java Sea, Indonesia, Proceedings of the Indonesian Petroleum Association, 21/1, 417-453.

Coffield, D.Q., Bergman, S.C., Garrard, R.A., Guritno, N., Robinson, N.M. and Talbot, J., 1993, Tectonic and stratigraphic evolution of the Kalosi PSC area and associated development of a Tertiary petroleum system, south Sulawesi, Indonesia, Proceedings of the Indonesian Petroleum Association, 22/1, 679-706.

Crotty, K.J. and Engelhardt, D.W., 1993, Larger foraminifera and palynomorphs of the upper Malawa and lower Tonasa Formations, southwestern Sulawesi Island, Indonesia. Thanasuthipitak, T. (ed.) Symposium on biostratigraphy of mainland Southeast Asia: Facies and Paleontology, 31 January - 5 February, Chiang Mai, Thailand, 71-82.

Cucci, M.A. and Clark, M.H., 1993, Sequence stratigraphy of a Miocene Carbonate Buildup, Java Sea. Loucks, R.G. and Sarg, J.F. (eds.), Carbonate sequence stratigraphy, recent developments and applications. American Association of Petroleum Geologist, Memoir, 57, 291-303.

Dickey, P.A., 1986, Petroleum Development Geology, Penwell Publishing Co, (3rd Edition), 530 p.

Fulthorpe, C.S. and Schlanger, S.O., 1989, Paleo-oceanographic and tectonic settings of early Miocene reefs and associated carbonates of offshore southeast Asia, American Association of Petroleum Geologists Bulletin, 73, (6), 729-756.

Grainge, A.M. and Davies, K.G., 1983, Reef exploration in the east Sengkang basin, Sulawesi, Indonesia, Proceedings of the Indonesian Petroleum Association, 12/1, 207-227.

Hamilton, W., 1979, Tectonics of the Indonesian region, United States Geological Survey Professional Paper, 1078.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith., A.G. and Smith D.G., 1990, A geologic time scale 1989, Cambridge University Press, 236 p.

Hasan, K., 1991, The Upper Cretaceous flysch succession of the Balangbaru Formation, Southwest-Sulawesi, Proceedings of the Indonesian Petroleum Association, 20/1, 183-208.

Kohar, A., 1985, Seismic expression of late Eocene carbonate build-up features in the JS25 and P. Sepanjang trend, Kangean Block, Proceedings of the Indonesian Petroleum Association, 14/1, 437-452.

Longman, M.W., 1985, Fracture porosity in reef talus of a Miocene pinnacle-reef reservoir, Nido B Field, the Philippines, Roehl, P.O. and Choquette, P.W. (eds), Carbonate Petroleum Reservoirs, Springer-Verlag, Berlin, 547-561.

Mayall, M.J. and Cox, M., 1988, Deposition and diagenesis of Miocene limestones, Sengkang Basin, Sulawesi, Indonesia, Sedimentary Geology, 59, 77-92

McArthur, A.C. and Helm, R.B., 1982, Miocene carbonate buildups, offshore North Sumatra, Proceedings of the Indonesian Petroleum Association, 11/1, 127-146.

Park, R.K., Matter, A., Tonkin, P.C., 1995, Porosity evolution in the Batu Raja carbonates of the Sunda Basin - Windows of Opportunity, Proceedings of the Indonesian Petroleum Association, 24/1, 163-184.

Parkinson, C.D., 1991, The petrology, structure and geologic history of the metamorphic rocks of central Sulawesi, Indonesia, Ph.D. Thesis, University of London, 337 p.

Phillips, T.L., Noble, R.A. and Sinartio, F.F., 1991, Origin of hydrocarbons, Kangean Block, Northern Platform, offshore N.E. Java Sea, Proceedings of the Indonesian Petroleum Association, 20/1, 637-661.

Rose, R., 1983, Miocene carbonate rocks of Sibolga Basin, Northwest Sumatra, Proceedings of the Indonesian Petroleum Association, 12/1, 107-125.

Siemers, C.T., Deckelman, J.A., Brown, A.A, and West, E.R., 1992, Characteristics of the fractured Ngimbang carbonate (Eocene), West Kangean-2 well, Kangean PSC, East Java Sea, Indonesia. Siemers, C.T., Longman, M.W., Park, R.K. and Kaldi, J.G. (eds.), Carbonate rocks and reservoirs of Indonesia, Indonesian Petroleum Association Core Workshop Notes, 1, Ch. 10.

Sukamto, R., 1975, The structure of Sulawesi in the light of plate tectonics, Paper presented at regional conference on the Geology and mineral resources of SE Asia, Jakarta, August 4-7, 1-25.

Sukamto, R., 1982, Geologi lembar Pangkajene dan Watampone bagian barat, Sulawesi, Geological Research and Development Centre.

Sukamto, R. and Supriatna, S., 1982, Geologi lembar Ujung Pandang, Benteng dan Sinjai quadrangles, Sulawesi, Geological Research and Development Center.

Sun, S.Q. and Esteban, M., 1994, Paleoclimatic controls on sedimentation, diagenesis and reservoir quality: Lessons from Miocene carbonates, American Association of Petroleum Geologists, Bulletin, 74, (4), 519-543.

van de Weerd, A.A. and Armin, R.A., 1992, Origin and evolution of the Tertiary hydrocarbon-bearing basins in Kalimantan (Borneo), Indonesia, American Association of Petroleum Geologists Bulletin, 76, (11, November), 1778-1803.

van Leeuwen, T.M., 1981, The geology of southwest Sulawesi with special reference to the Biru area. Barber, A.J. and Wiryosujono, S. (eds), The Geology and Tectonics of Eastern Indonesia, Geological Research and Development Centre, Bandung, Special Publication, 2, 277-304.

Wilson, M.E.J., 1995, The Tonasa Limestone Formation, Sulawesi, Indonesia: Development of a Tertiary Carbonate Platform, Ph.D. Thesis, University of London, 520 p.

Wilson, M.E.J., 1996, The Geology of Sulawesi with special reference to western Sulawesi, University of London Geological Research in Southeast Asia Internal Report, 135, 72 p.

Wilson, M.E.J. and Bosence, D.W.J., 1996, The Tertiary Evolution of South Sulawesi: A Record in Redeposited Carbonates of the Tonasa Limestone Formation, In: Hall, R. and Blundell, D.J. (eds.), Tectonic evolution of SE Asia. Geological Society of London Special Publication, No.106, 365-389.

Wilson, M.E.J. and Bosence, D.W.J., in press, Platform Top and Ramp deposits of the Tonasa Carbonate Platform, Sulawesi, Indonesia. In: Fraser, A. (ed.), Petroleum exploration of SE Asia, Geological Society of London Special Publication, in press.

Wilson, M.E.J., Rosen, B., and Ngakan, A., 1996, Palaeogene scarcity of corals and reefs in SE Asia: A major problem for the center of origin idea Biogeography and geological evolution of SE Asia, Abstracts volume.

Yuwono, Y.S, Maury, R.C., Soeria-Atmadja, P. and Bellon, H., 1987, Tertiary and Quaternary geodynamic evolution of South Sulawesi: Constraints from the study of volcanic units, Geologi Indonesia, 13, (1), 32-48.

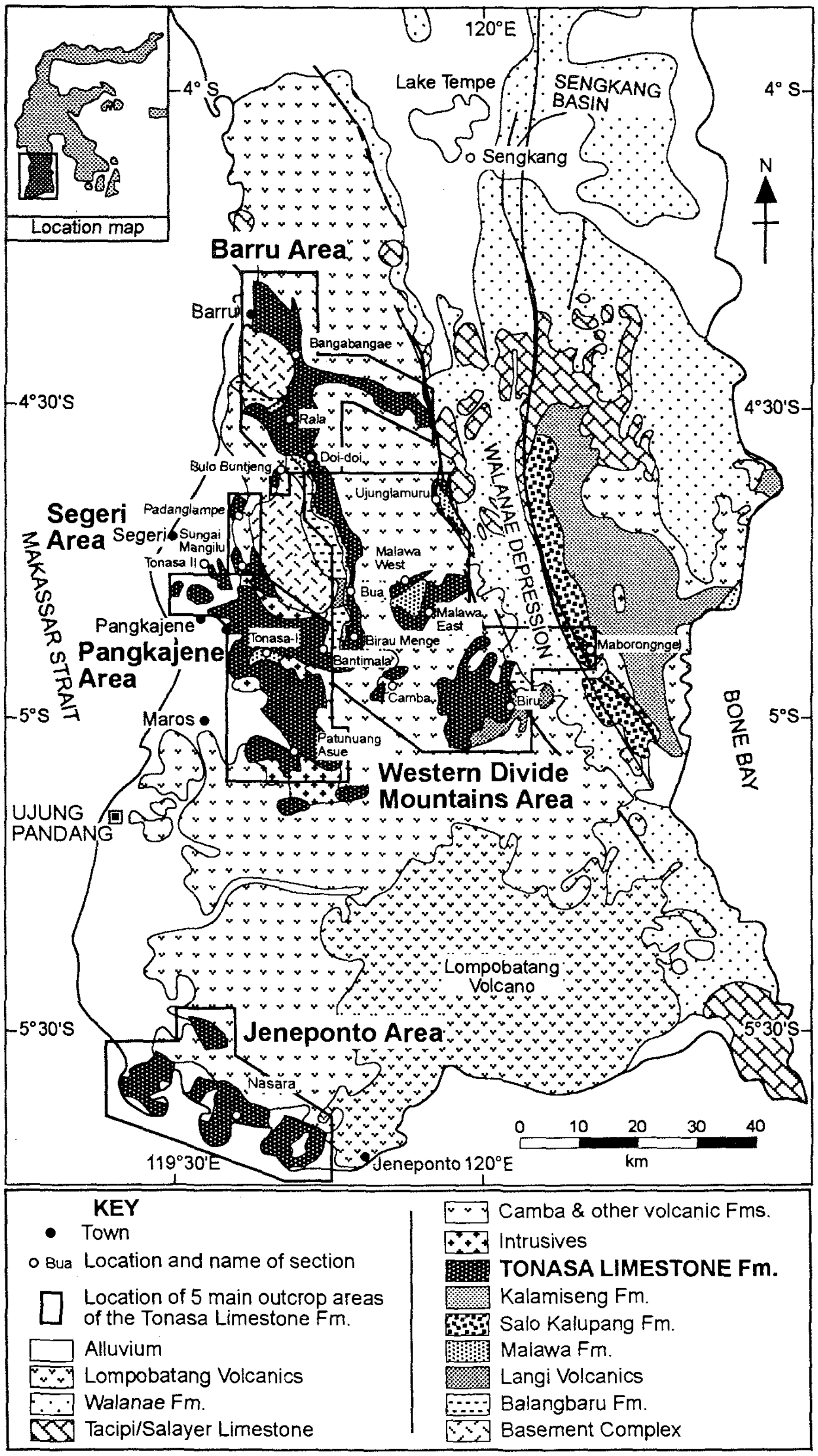

FIGURE 1 - Geological map of South Sulawesi (after van Leeuwen, 1981; Sukamto, 1982; Sukamto & Supriatna, 1982), showing the locations of the 5 main outcrop areas of the Tonasa Limestone Formation and the location of measured sections mentioned in the text.

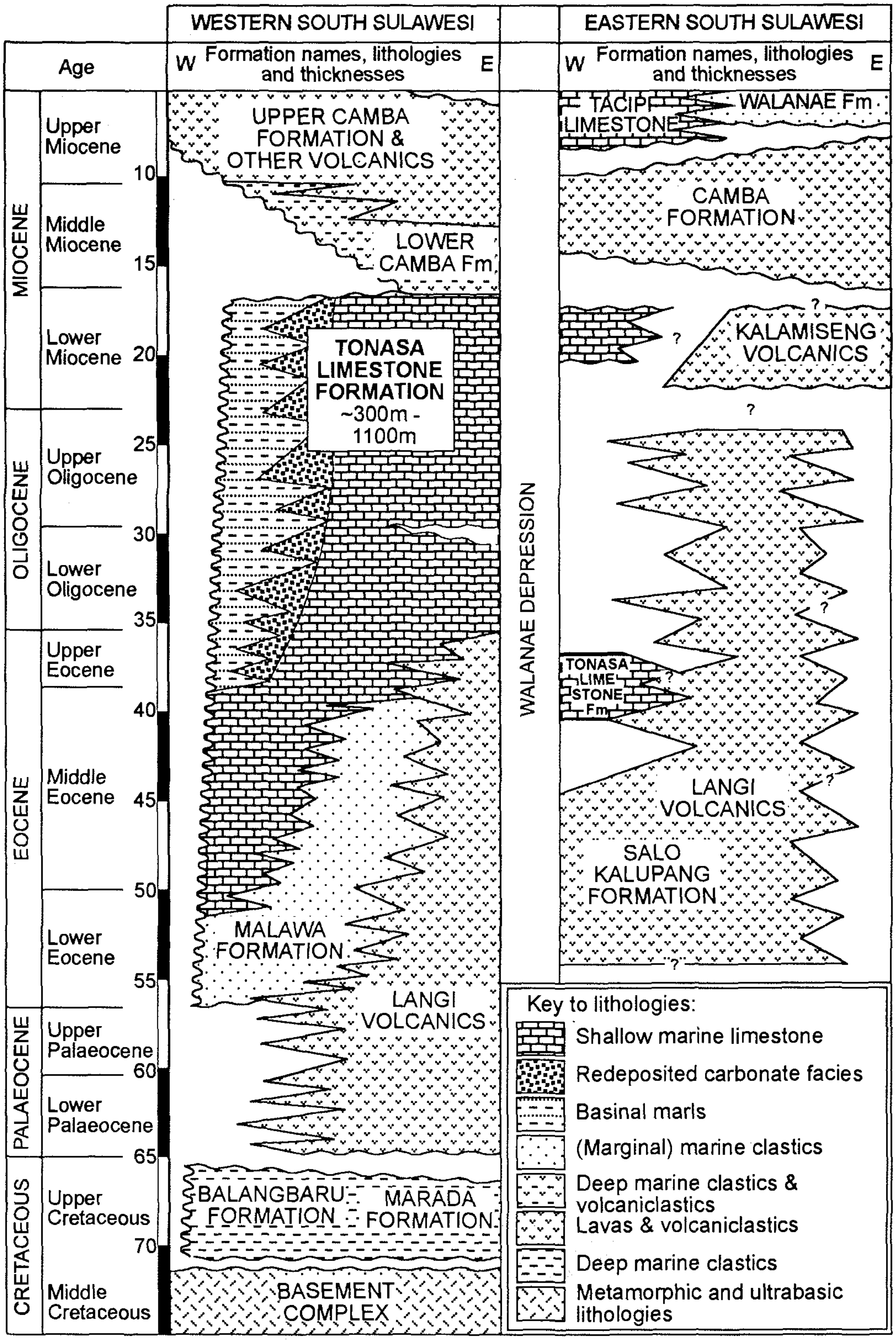

FIGURE 2 - Stratigraphic correlation chart of the units to the west and east of the Walanae Depression in South Sulawesi (after van Leeuwen, 1981; Sukamto, 1982; Sukamto & Supriatna, 1982 and Grainge & Davies, 1983). Time scale after Harland, et al. (1990).

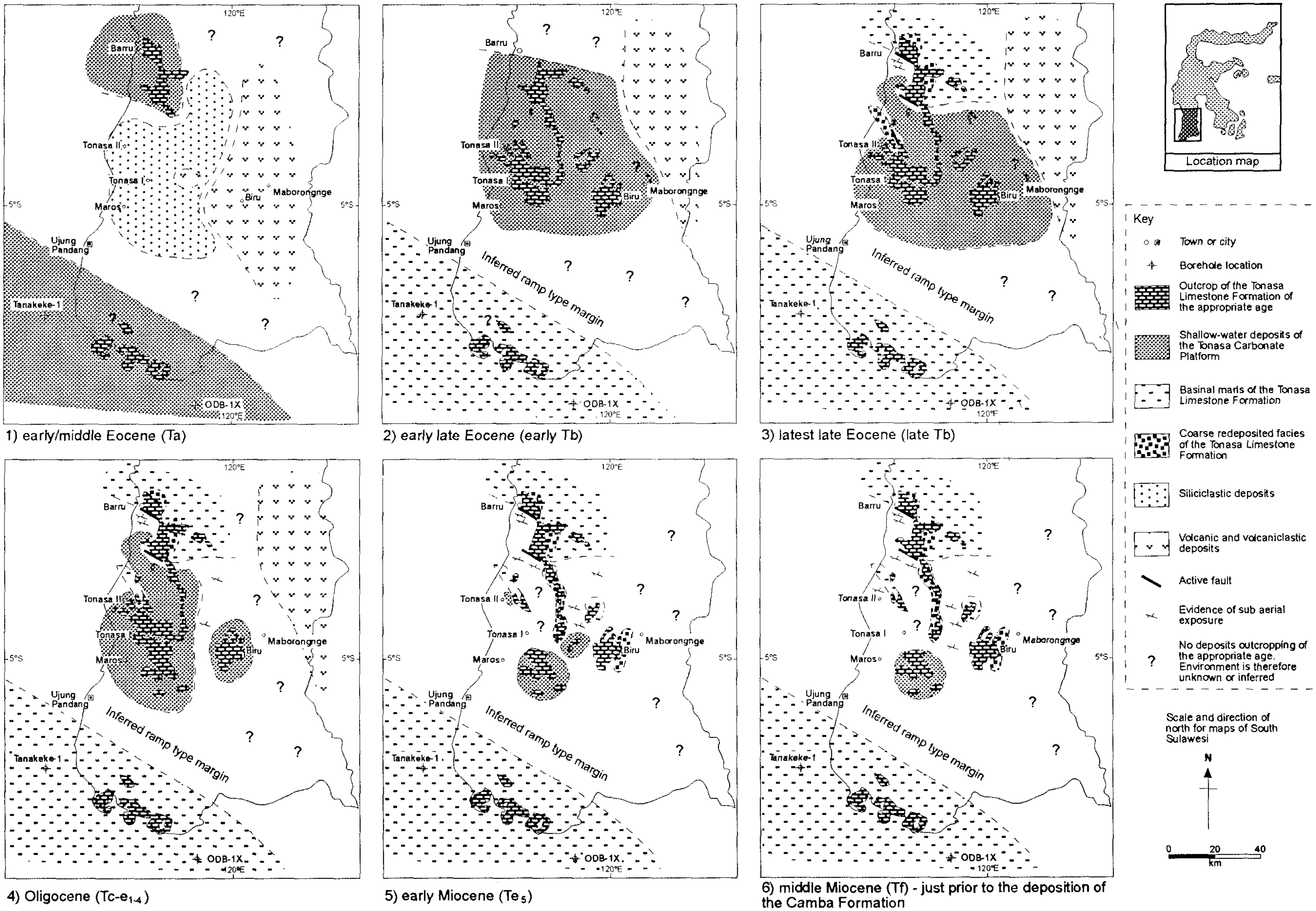

FIGURE 3 - Simplified palaeogeography maps of South Sulawesi from the early/middle Eocene to the middle Miocene during the deposition of the Tonasa Limestone Formation. Not rotated for palaeomagnetic data.

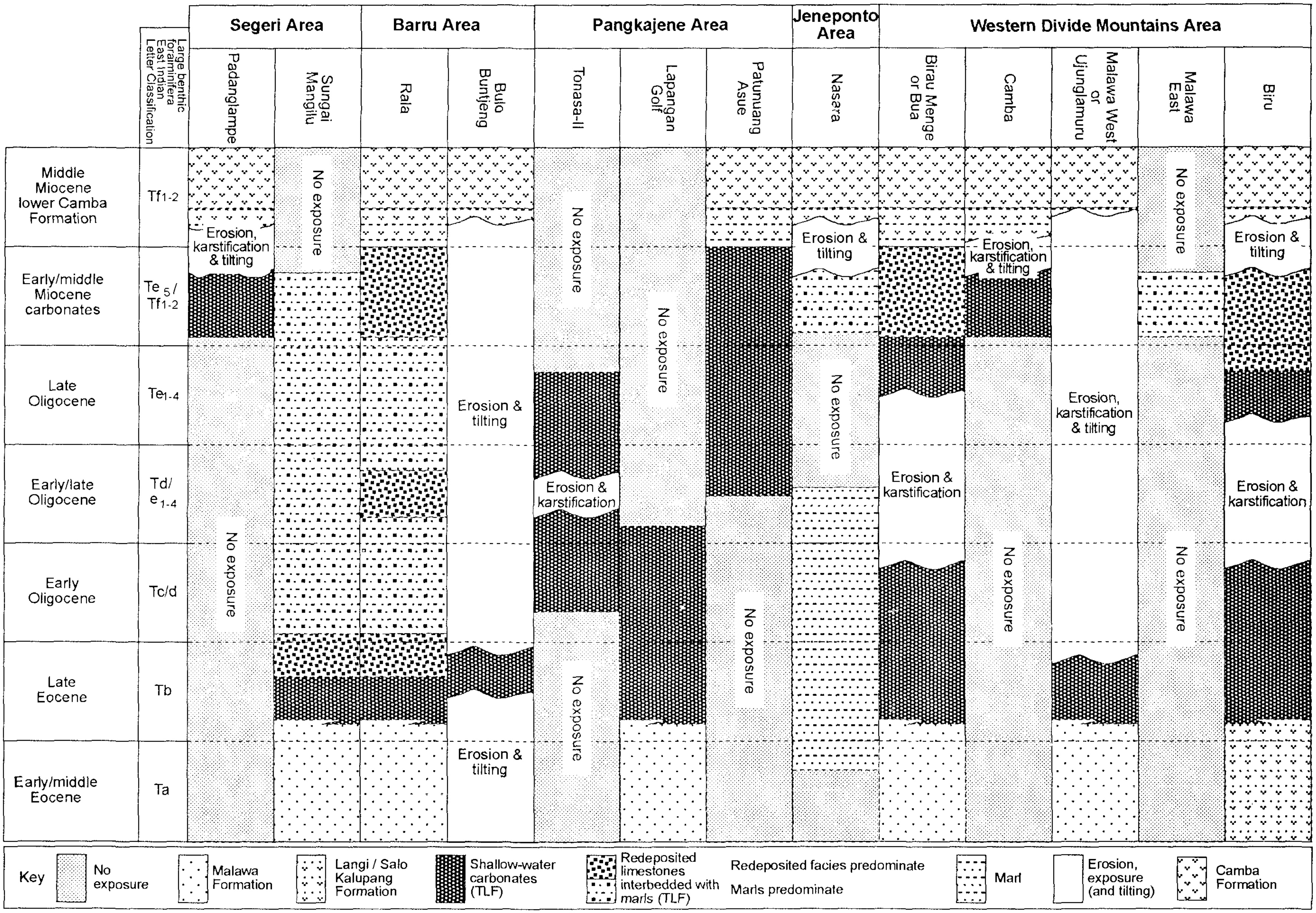

FIGURE 4 - Early/middle Eocene to middle Miocene depositional (and non-depositional) history of the Tonasa Limestone Formation in its outcrop areas in South Sulawesi.

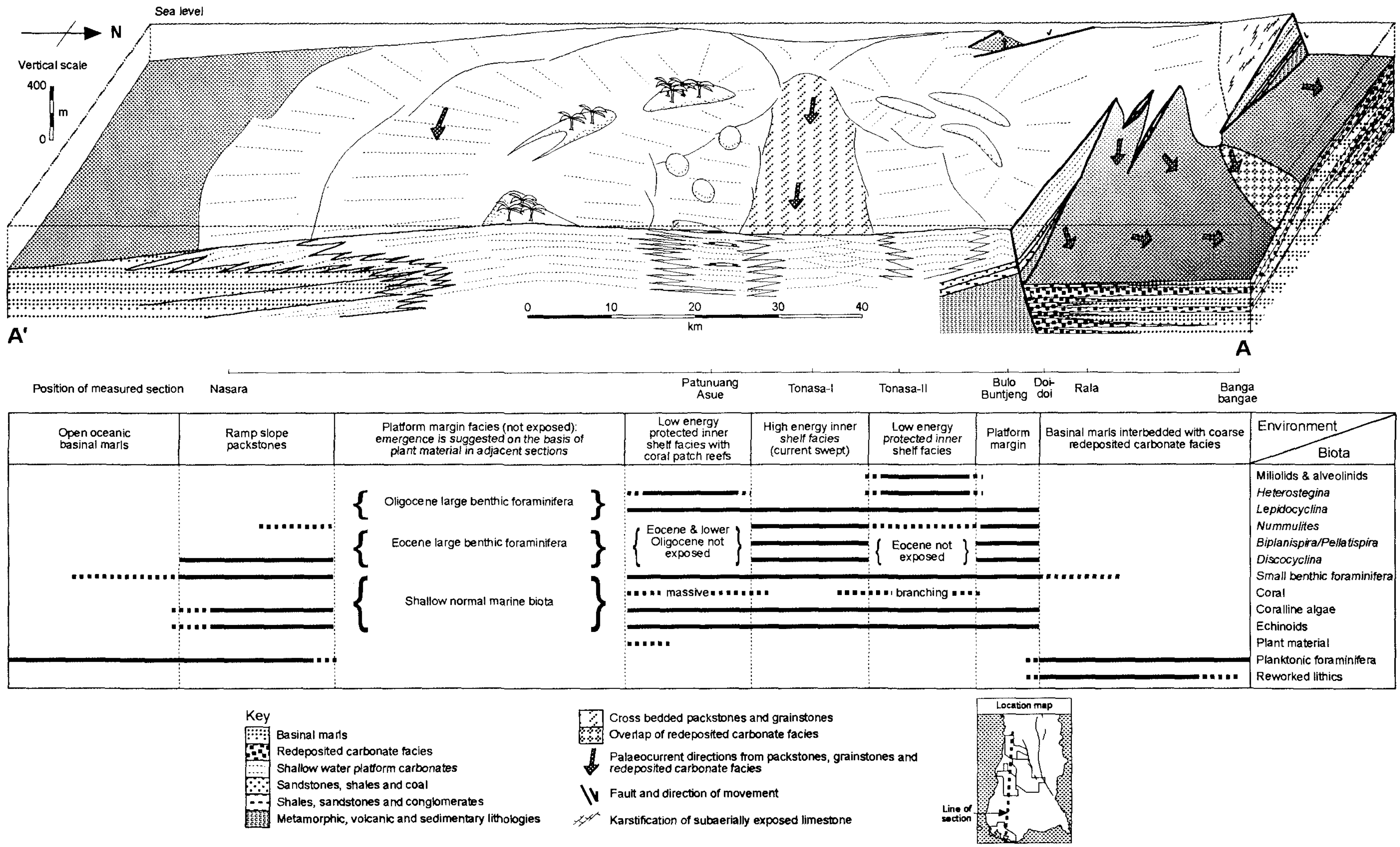

FIGURE 5 - North/south block diagram through the Tonasa Carbonate Platform showing the central Pangkajene, northern Barru, southern Jeneponto and western Padanglampe Areas, during the late Eocene or Oligocene. The distribution of biota across the platform is also shown.