Geohistory analysis of South Makassar

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ABSTRACT

A quantitative approach to stratigraphy shows how the south Makassar Straits Basin developed, and how the major sequences of sediment were deposited. After the initial rifting of the grabens there were four major, basin changing, unconformities that strongly affected sedimentation; at about 39 Ma (later Middle Eocene), 36 Ma (early part of Late Eocene), 34 Ma (almost on the Eocene to Oligocene boundary) and about 24 Ma (almost at the Oligocene-Miocene boundary).

The 39 Ma event saw accelerated rifting on the distal margins of Sundaland, in the south and southeast. The 36 Ma event is very strongly expressed in the South Makassar area and is shown by the geohistory analysis to have included basement subsiding by as much as 2 kilometres in 2 million years. The 34 Ma event led to the onset of the Berai Limestone to the west and very strongly reduced rates of deep-water sedimentation throughout the Makassar to Spermonde area. The c. 24 Ma event saw a substantial change in sedimentary conditions, with the end of condensed deep marine clastics and shallow marine Berai carbonates, and the start of a new clastic phase with high rates of sedimentation. These times of major change are all thought to be controlled by tectonism, because their magnitude exceeds rates of eustatic change, and also because their geographic expression is highly variable.

The first rift phase contains important lacustrine hydrocarbon source rocks in the inland areas of Sundaland, and large deltas with coaly sources on the fringes of the continent. The subsidence and associated sediment supply history has impact on the later deposition of coaly deltas, and the accumulation of overburden and thermal maturity of buried sediments.

Keywords: geohistory analysis, south Makassar, Makassar Straits.

INTRODUCTION

Many wells in the south Makassar Straits have their largest and most abrupt contrast in environmental indicators within the Eocene section, showing a sudden and strong transgression to fully bathyal conditions. This review examines four wells using geohistory techniques (van Hinte, 1978) to quantify this major change. It also considers the implications from this stratigraphic analysis on the large scale, basin architecture-related, sequences of sedimentation.

The Pangkat-1 [P-1] well drilled the complete Eocene to Recent sedimentary succession in the West Makassar Graben (Figures 1 & 3), reaching Cretaceous igneous basement at total depth [TD]. It is possible to carry out geohistory analysis from published well data (Djamil and Bani, 2005; Pireno et al., 2009; Kupecz et al., 2013). However this well was drilled on a palaeo-high, and therefore the lowest part of the graben-fill is condensed. To compensate for this, analysis can be extrapolated to the adjacent Makassar Straits-1 [MS-1] well, which drilled the graben centre but stopped within the Late Eocene sediments. Analysis at MS-1 can be extended to basement using published seismic data, tied to P-1, and a velocity - depth function to estimate the deepest section between drilled TD and basement.

The seismic line through P-1 and MS-1 crossing the West Makassar Graben, and almost reaching Takatalu-2 [TT-2] in the NE, was described in Djamil and Bani (2005), Figure 3 here. This graben is a branch of the south Makassar Straits rift basin (see Figure 10 in Kupecz et al., 2013). On the cross-section (*cf.* Figure 6 of Djamil and Bani, 2005, and Figure 3 here) some of the sedimentary facies, such as biohermal reefs and lacustrine muds, have been proven by wells, and these facies also have distinct seismic character. The inversion anticline drilled by the MS-1 has folded a deep marine carbonate debris-flow described in Pireno et al. (2009). This is the trap and reservoir for the Ruby Gas Field. However, in contrast to these seismically distinct facies, the majority of sediments in the wells, and in the plane of the cross-section, are deep marine claystones. It is the contrast between non-marine sediments, the first marine transgression, later deep marine deposition, and the shallow marine reefs outside the graben, that is the subject of this review.

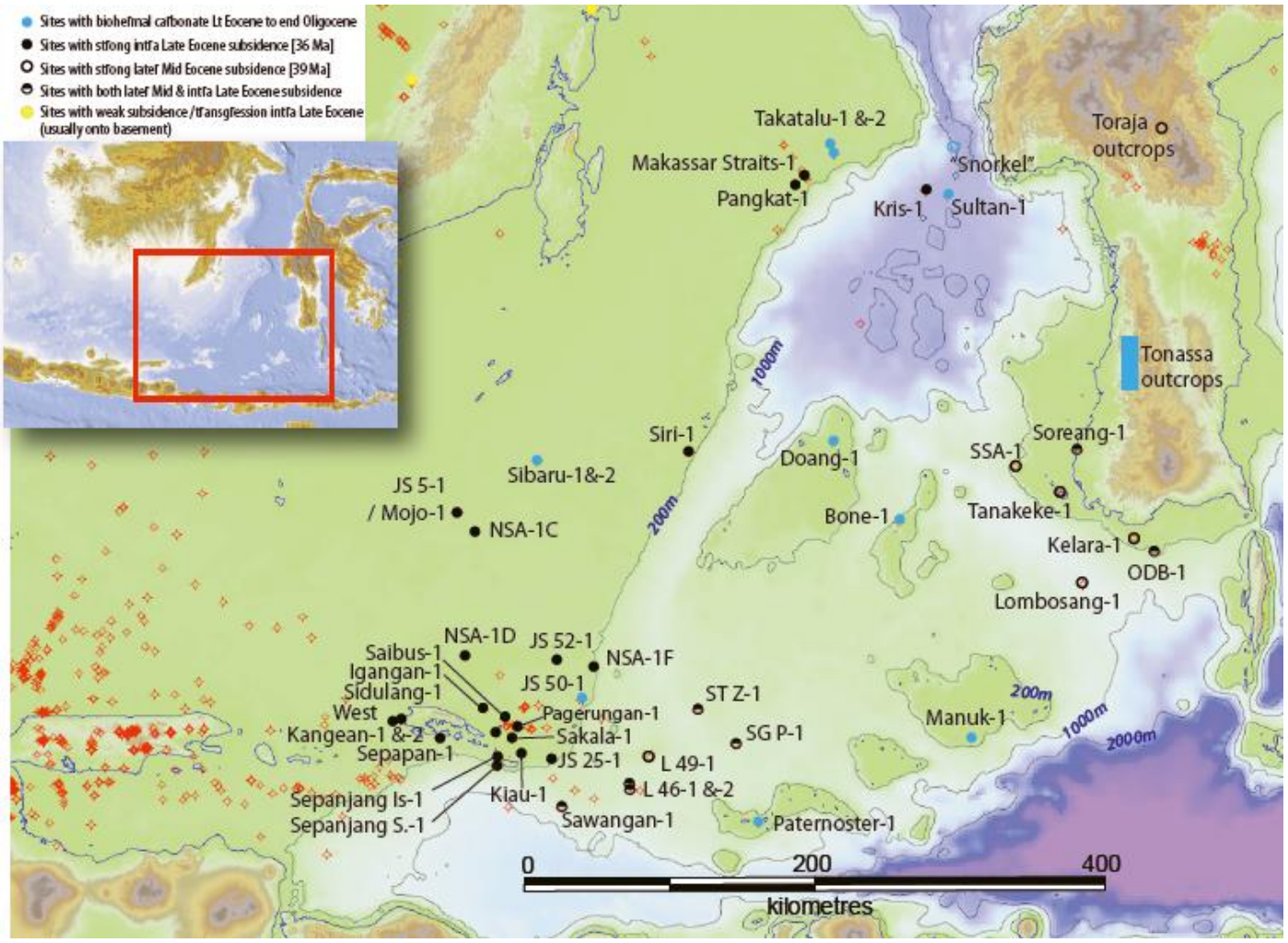


Figure 1. *Location map.*

This study also contrasts the geohistory of the West Makassar Graben with the Spermonde Graben to the south and, for comparison, the relatively stable horst of the Doang-Bone Platform. The Lombosang-1 [L-1] well drilled the centre of the Spermonde Graben, at present water depths of almost 1000m. Considerable and sudden subsidence is noted there, but at a different time to the main event in the West Makassar Graben. The Bone-1 well [B-1] on the stable, horst, platform naturally shows much less subsidence, and this well drilled shallow marine carbonate for almost the entire section. Even in this well there is an Oligo-Miocene stratigraphic anomaly that may be correlatable to the other wells.

GEOHISTORY ANALYSIS PANGKAT-1

The geohistory diagram (Figure 2) begins with lacustrine sediments deposited over Cretaceous andesitic basement. Oil, sourced from this lacustrine unit, was tested out of the weathered basement. At the well location these organic-rich beds were laid down over a palaeo-high within an ancient lake, which extended all around the P-1 location. The seismic response associated with this facies is a distinct package of strong, continuous parallel reflectors that is typical for organic lacustrine beds (*cf*. seismic in Sukanto et al., 1998; Asri Basin of SE Sumatra). This unit is difficult to date as the palynoflora is dominated by freshwater *Botryococcus* & *Pediastrum* algae, and has sparse age diagnostic flora or fauna. The presence of *Meyeripollis naharkotensis* down to the deepest sample (2414m) is indicative of an age no older than Late Eocene for a substantial part of this section (some caving into deeper samples is possible). The lowest marine beds immediately overlying the distinct lacustrine facies contain the dinoflagellate *Duosphaeridium nudum* (a Middle Eocene restricted taxon, Williams & Bujak, 1985), and *Glaphyrocysta ordinata* (extinction near top Middle Eocene, Williams & Bujak, 1985), both present as single specimens. In the next 60m of mudstone above this initial marine transgression silty mudstones are found with *Nummulites* and *Pellatispira* that in this, and other wells nearby, are dated as Tb Letter Stage (see illustrations of advanced *Pellatispira* species in the TT-1 biostratigraphy report) The Tb Letter Stage is roughly equivalent to the Late Eocene (the Middle to Late Eocene boundary here being defined on the top Ta and P14 mass extinction of various larger and planktonic foraminifera at about 37 Ma; Berggren et al., 1995, Lunt & Allan, 2004, GTS04).

At about 2286m measured depth in this well there is a marked log-break reflecting an abrupt change in lithology. Overlying this event the mudstones are rich in planktonic foraminifera as well as fully

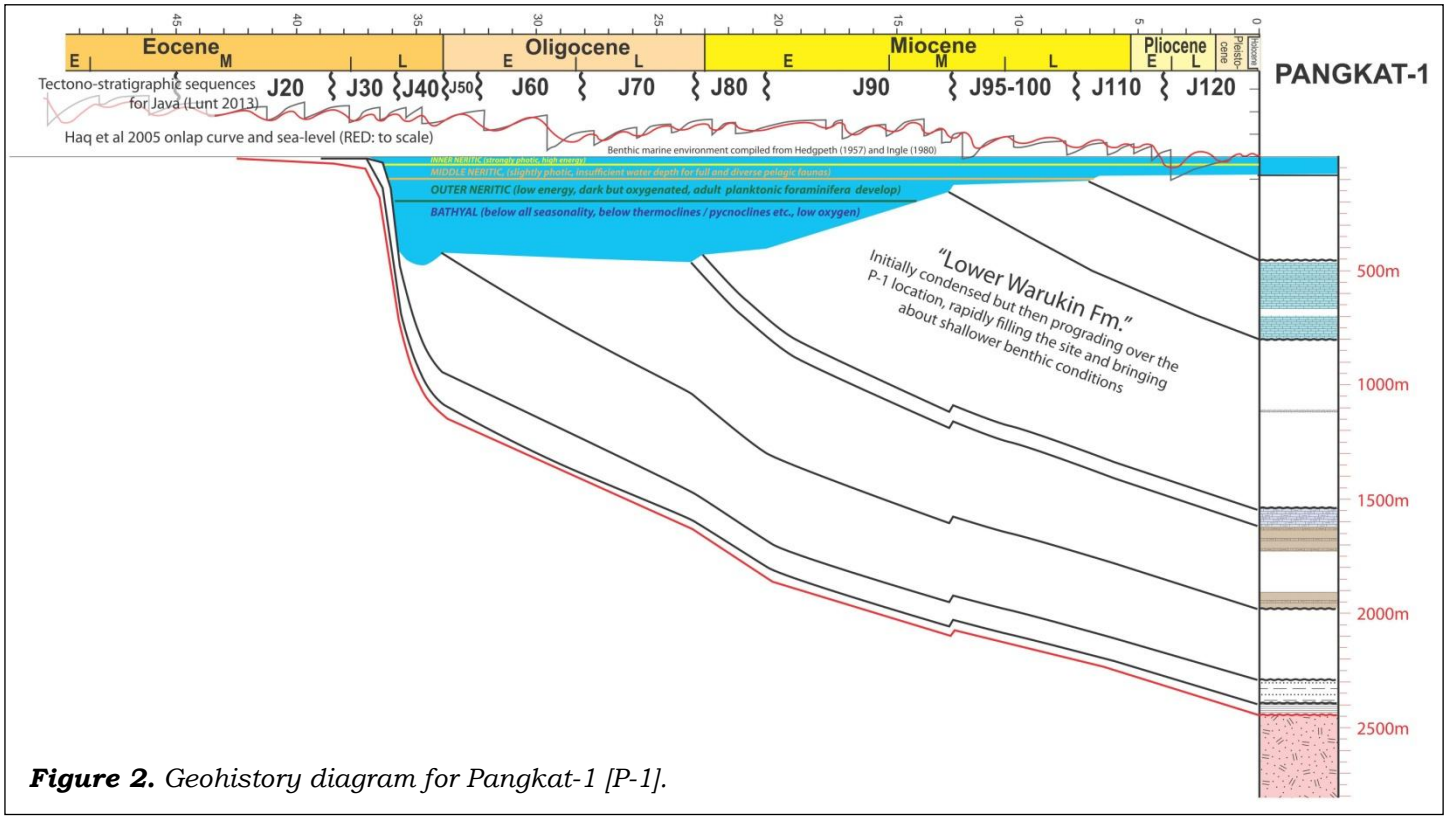


Figure 2. *Geohistory diagram for Pangkat-1 [P-1].*

bathyal benthic foraminifera such as *Planulina wuellerstorfi*, several *Melonis* species, *Osangularia* species, *Gyroidina soldanii, Globobulimina pyrula, Uvigerina peregrina* and *Cyclammina* species. Late Eocene planktonic foraminifera and nannofossils are found as high as 1963m, which is the P17 / NP20 extinction event [c 33.8 to 34.0 Ma, Gradstein et al., 2004; Wade et al., 2011]. Deep marine (deep outer neritic to upper bathyal) conditions continued up hole and through time to at least the end of the Oligocene (about 1524m MD), above this depth a new and accelerated influx of prograding clastic sediments (cf. Kupecz et al., 2013, Figure 18) led to gradually shallowing of the sea floor at this site, leading to the present mid-middle neritic setting (64m water depth). In the younger section there is, at least, one uplift associated with inversion of the graben-defining fault, which is why the correlations deeper in the wells are referenced to the top Eocene event. At P-1 there could have been two slight uplift/ relative sea-level fall events, at about 790m and 427m in the well. Later Pliocene to Recent sea-level fluctuations may have occasionally reduced this site to an inner neritic setting (less than 20m).

Although it is sensitive to the sediment compaction calculation, the geohistory diagram shows the transition from bathyal to neritic conditions at P-1 (uphole; c. 200m water depth; Hedgpeth, 1957 & Ingle, 1980) occurred during deposition of the Lower Warukin Formation. This matches the transition based on benthic fossil assemblages, which therefore gives some confidence in the proposed basement subsidence curve for the past 15 Ma (Figure 2).

Therefore the first problem for this geohistory review is to estimate how deep and how fast basement at P-1 subsided. This is a balance between an initial sudden subsidence and a later, longer, "sag" phase. As noted above, the contrast in environment-related benthic fauna is, by far, greatest at the 36 Ma event in the well samples. The noted changes at about 790m and 427m (mid Miocene) are slight regressive events, of much smaller magnitude than the 36 Ma contrast. A review of other wells reaching Eocene or basement in this area has found that many wells in the southern Makassar Straits have by far their largest palaeoenvironmental shift in their sedimentary history within the early part of the Late Eocene, soon after transgression over basement. This transgression led to bathyal deposition almost immediately overlying basement or very thin inner neritic facies.

GEOHISTORY ANALYSIS OF MAKASSAR STRAITS-1

The cross section (Figure 3) shows that during the first rift phase the organic rich lacustrine deposits, with their distinct acoustic / seismic response, thickened into the graben, as did the subsequent transgressive, shallow marine clastics (it does not affect the calculation here if such thicker transgressive deposits are considered deeper marine in the graben than those sampled by P-1). The key feature at the MS-1 location is the correlation to the abrupt lithofacies change at 2286m MD in P-1, the 36 Ma onset of bathyal deposition, which is between 2965m and 3258m ss in MS-1. The deeper number is the author's preferred seismic correlation and will be used in the estimates below, but it should be borne in mind that there are alternative seismic correlations

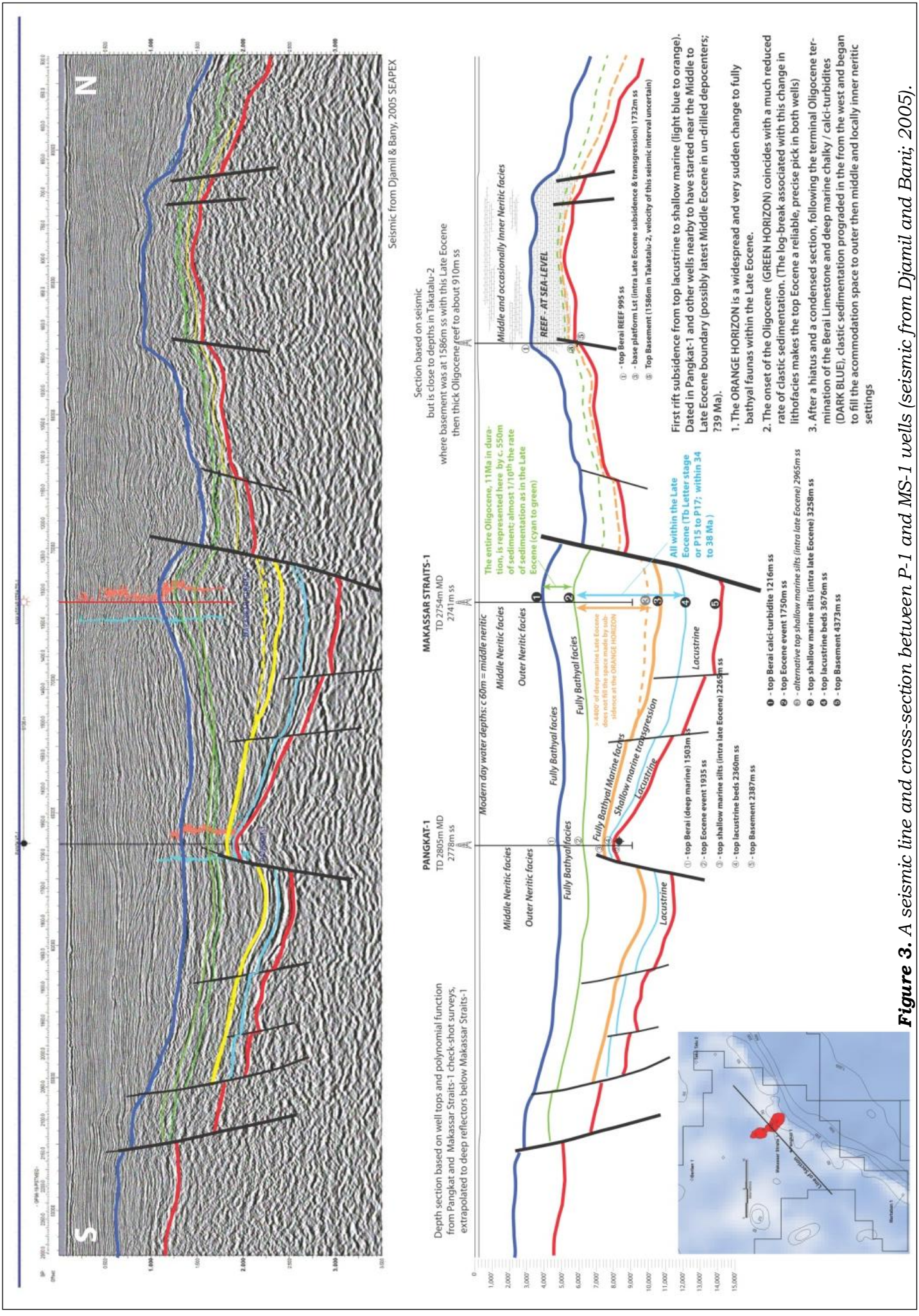


Figure 3. *A seismic line and cross-section between P-1 and MS-1 wells (seismic from Djamil and Bani; 2005).*

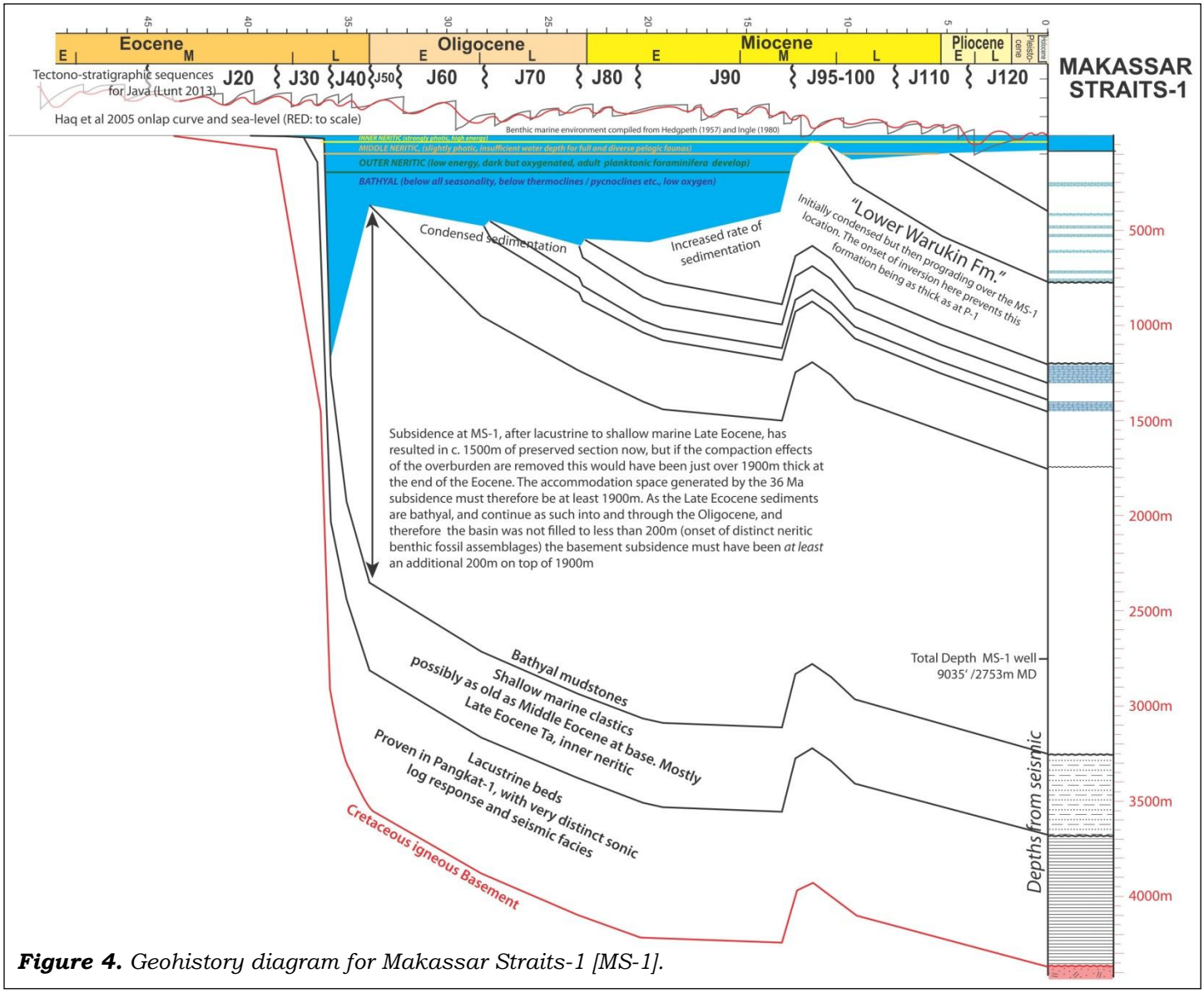


Figure 4. *Geohistory diagram for Makassar Straits-1 [MS-1].*

that could be as much as 300m shallower. The next sequence boundary above this seismically correlated event is one that was reached by drilling in the MS-1 well. In most wells in the south Makassar area, the Eocene to Oligocene boundary (c. 34 Ma) is marked by a log break with lower gamma ray response above, coinciding with the first appearance, downhole, of Eocene foraminifera and nannofossils in cuttings. This is a good correlation horizon to hang older Eocene stratigraphy from, as it is necessary to remove the thickness-changing effects of the mid- Miocene inversion, which formed the anticline drilled by MS-1. In P-1 the thickness of sediment from this top Eocene event to the 36 Ma log break is 323m. In MS-1 it is 1508m, of which 1004m was proved by drilling. From the top of lacustrine seismic reflectors there are 1920m of sediment, entirely Late Eocene, Letter Stage Tb, in age.

This data means that at about 36 Ma [top of the shallow marine strata] subsidence occurred, and a depocentre made, so that by the end of the Eocene (c. 34 Ma) at least 1508m of sediment was deposited, but this sediment did not fill the depocentre to sea-level. In fact it did not even fill it to within 200m of sea-level, above which depth some outer neritic assemblages would be expected to have been seen in MS-1 palaeontological analysis. This simple arithmetic does not take into account the effect of sediment compaction, which is shown on the geohistory diagram (Figure 4). Removing the effects of post-Eocene overburden compaction, the actual thickness of Late Eocene sediments above the transgression, at the end of the Eocene, was about 1920m (calculation from Genesis modelling software). Therefore at the very least, basement subsidence must have been a minimum of about 2100m needed to keep the benthos out of neritic influences, within 2 Ma.

The cross-section from MS-1 to the carbonate platform in the NE (Figure 3) also gives geohistory data. While velocities in the limestone will differ from the claystone-rich data used to convert the P-1 and MS-1 area there is additional well control from the TT-2 well a short distance to the NE (Djamil and Bani, 2005; Kupecz et al., 2013). Both the seismic data and this well have the near end Oligocene termination of the Berai Limestone reef deposition (which is the same age as the terminal debris carbonate in the MS-1, Pireno et al., 2009)

at a depth of 990m. Also the first, intra Late Eocene marine transgression over basement is at 1585m in TT-2 (there are good photographs of Tb diagnostic fossils in the biostratigraphy report for this well). What this shows is that the correlative first marine transgression, occurring slightly before the 36 Ma subsidence, would have been offset in the graben by the amount of throw on the graben-defining faults. Being located on the horst, only much more gentle, long-term subsidence was seen at TT-2, like Bone-1 and Doang-1 wells to the south.

So the transgression horizon at 1585m in TT-2 is now displaced to 3258m at MS-1, a vertical offset of 1673m. The vertical displacement relative to Pangkat-1 is 700m. This simple subtraction is not affected by sediment compaction, and is just the fault displacement remaining now, without considering the fault inversion in the middle Miocene, which produced the fold at MS-1. Inversion uplift is thought to be negligible at Pangkat-1 as it is outside the fold drilled at MS-1, but sudden slight uplift in mid Miocene times is noted in the P-1 well section. It is hard to estimate, and thereby compensate for, the amount of inversion movement at MS-1 from the seismic and cross-section because the anticline at MS-1 is a "Sunda fold" (Eubank & Makki, 1981). In such structures shallower beds are folded more than deeper strata, and fault movement is not a simple vertical vector. The top Oligocene, top Berai equivalent, and overlying beds have been uplifted by about 640m to form the anticline at MS-1. Uplift of the unfolded Eocene horizons may have been only a fraction of this. The value of this cross-sectional estimate is that even though it cannot differentiate Eocene subsidence from any later sag, or the known inversion uplift, it supports the earlier estimation that the West Makassar Graben has seen over a kilometre and a half of subsidence, which the first method suggests was mostly within the short-lived Late Eocene.

GEOHISTORY ANALYSIS OF LOMBOSANG-1

The Lombosang-1 [L-1] was drilled in 2003 in 939m water depth (Figure 5). Samples at TD, not reached by logging tools, had high vitrinite reflectance indicative of metasedimentary basement. Seismic also indicates basement at TD. Like Pangkat-1 this well was drilled on a palaeo-high so the very oldest Cenozoic sediments were not sampled by the well. The deepest samples are non-marine and contain only general Cenozoic palynomorphs. About 200m above basement the well samples contain Middle Eocene and younger *Florschuetzia* pollen and there is a further 800m of lower coastal plain to paralic sedimentary section indicating both significant graben subsidence already within the Middle Eocene (see shallower age constraints below), as well as a high rate of sedimentation. At about 2550 to 2650m in the well there are well bedded coals, visible on wireline logs, and on the seismic data over a wide area in

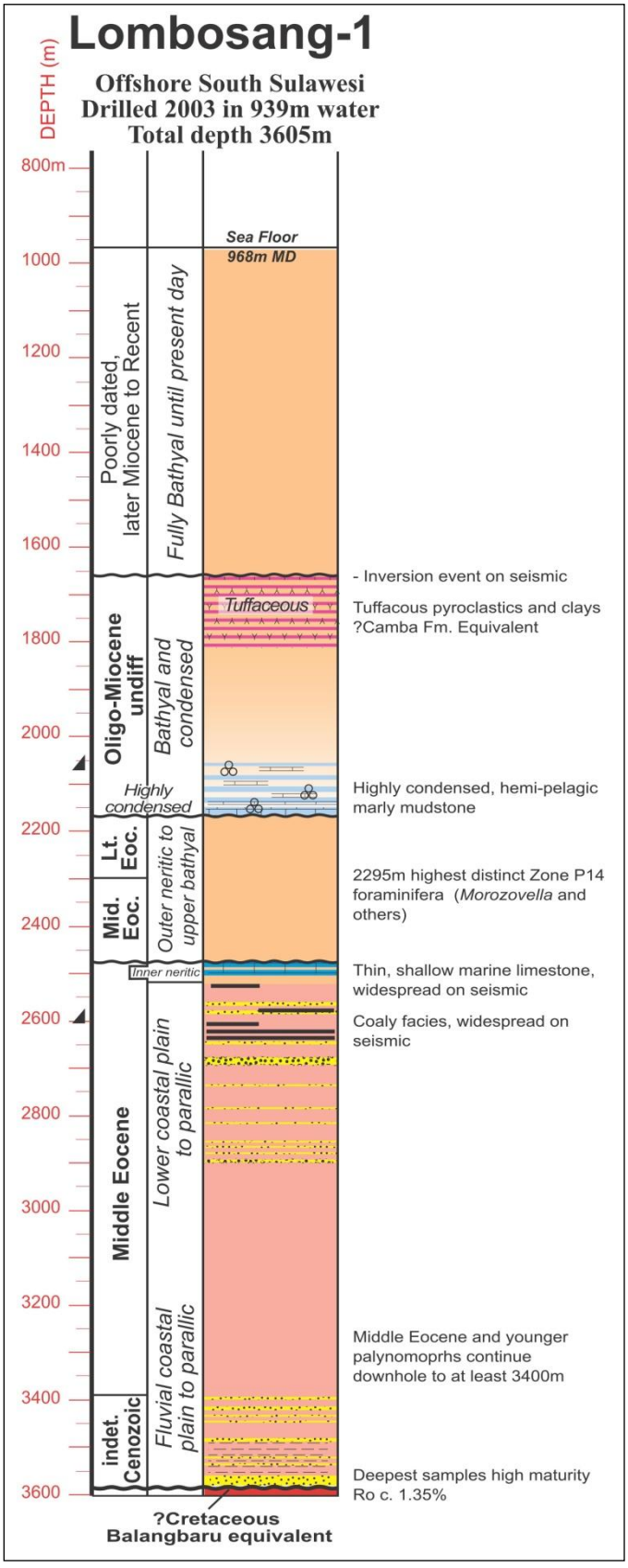


Figure 5. *Stratigraphic summary of Lombosang-1.*

the Spermonde Graben.

Above the coaly section there are less than 50m of marine beds with shallow marine limestone, containing larger foraminifera. At 2480m sample depth (1513m below the present sea floor) there is a log break at the top of shallow marine limestones. Above this there are deep marine mudstones (outer neritic to upper bathyal, passing

upwards into fully bathyal) with morphologically distinct P14 [and older] planktonic foraminifera. These are the keeled Morozovellid forams which became extinct at 38 Ma (Wade et al., 2011).

Bathyal sediments are present uphole for the rest of the well that was sampled, continuing to the present day sea-floor conditions at 939m depth. Put simply, paralic coals deposited slightly above sea-level were initially transgressed by shallow, photic limestones and then were suddenly subsided to very deep marine conditions, where they have stayed ever since.

The geohistory diagram for this well (Figure 6) is less constrained than MS-1 where a known thickness of later Eocene sediment requires a greater accommodation space to have been formed to contain it. At L-1 the ages of the non-marine sediments is poorly known, allowing the far-left data points on the geohistory diagram to have a range of possible positions along the X axis. The unknown thickness of the water column after subsidence (unlike MS-1) allows flexibility in how these points are plotted along the vertical, Y axis. It is possible to draw the diagram so the basement subsidence curve is a single trend, starting in early Middle Eocene times, and it was only at about 39 Ma that subsidence exceeded sediment supply resulting in rapid marine transgression. A comparative review of all geohistory plots for all the wells in the area is required to assess this, including such wells as ODB-1x which did not reach basement but shows high rates of later Eocene bathyal sedimentation after the 39 Ma transgression/subsidence.

Perhaps the most important indicator that an abrupt acceleration event in a longer term subsidence occurred at about 39 Ma is the fact that over more than 100kms across the Spermonde Graben, and also in a second graben some 200 kms to the southwest, where the ST Z-1, SG P-1, L 46-1 &-2 and Sawangan-1 wells are located (Figure 1), a marked environmental contrast from shallow marine to very deep marine occurs one or two hundred meters below the zone P14 extinction datum. There is no sign of diachroneity, and some of the more distal wells such as ODB-1x and Kelara-1 have the thickest post 39 Ma Eocene marine sediment sections. It is also significant to note that Phillips et al. (1991) described, in this southwestern area, a marked angular unconformity between the older Middle Eocene “pre-Ngimbang” and the rapid marine transgression that occurred over it, post 39 Ma. The existence of such an angular unconformity at the same time as accelerated basement subsidence points to a regional tectonic event rather than a diachronous flood in steadily subsiding rifts.

GEOHISTORY ANALYSIS OF BONE-1

The Bone-1 [B-1] well drilled shallow marine carbonate, apart from a thin (<50m) clastic and coal section over weathered Cretaceous lavas at TD. As with other wells drilling the porous carbonate platforms (Doang-1, Manuk-1 and Paternoster-1) circulation was lost many times, and cuttings samples have numerous gaps. Unlike the other wells, the B-1 had a large number of sidewall cores taken and analysed for biostratigraphy, so a fairly reliable stratigraphic summary is possible.

The geohistory diagram (Figure 7) has been annotated with the main points of this analysis. In brief the later Miocene to Recent marker *Alveolinella quoyi* is seen in cuttings and sidewall cores down to 809m, below which there is either a considerably condensed section or an unconformity. The distinct older Miocene marker *Miogypsina* is not found at all in this well and when an influx of older foraminifera are recorded at 887m and below, only older nephrolepidine *Lepidocyclina* are found, which in the absence of *Miogypsina* suggests the carbonates here are already Late Oligocene in age. The Oligocene carbonates continue for most of the rest of the well section although in the very lowest part of the limestone some Eocene *Discocyclina* are recorded, and in the very deepest carbonate sample the latest Eocene index *Pellatispira*. Sampling conditions are too poor in both Doang-1 and Manuk-1 to contribute any useful data.

The paucity of Te5 and lower Tf in Bone-1 appears, based on initial review, to be paralleled by a reduced number of limestone outcrops of this age, relative to thick Oligocene and Late Eocene sections, in the Tonasa Limestone to the east (Wilson, 1995; who also noted a peak in downslope reworking of carbonate at this time), and in the carbonates of Takatalu-1 and -2 wells to the north.

SUBSIDENCE OVER A WIDER AREA

As noted above, the transgression of bathyal deposition almost immediately overlying basement or very thin inner neritic facies is seen in many wells in the southern Makassar Straits. This includes the Siri-1, NSA-1C, NSA-1D, NSA-1F, JS5/Mojo-1, Crystal-1, JS 52-1, Igangan-1, Saibus-1, Pagerungan wells, Sakala-1, East Sakala-1, JS 25-1, Kiau-1, Sepanjang Island-1, South Sepanjang-1, L-49-1, Sidulang-1, Sepapang-1, and West Kangean-1 and -2 (Figure 1). In all these wells this abrupt environmental change takes place within the Late Eocene Letter Stage Tb [c. 36 Ma], with thin larger foraminifera bearing limestones below and rich planktonic foraminifera in the mudstones above (see Phillips et al., 1991; Bransden & Matthews, 1992)

To the south, the Sawangan-1 well geohistory has a two-fold subsidence, from delta-plain to middle or shallow outer neritic within later Middle Miocene times (with P14 or P13), followed by a subsidence to fully bathyal conditions within P15, early Late Eocene [the 36 Ma event].

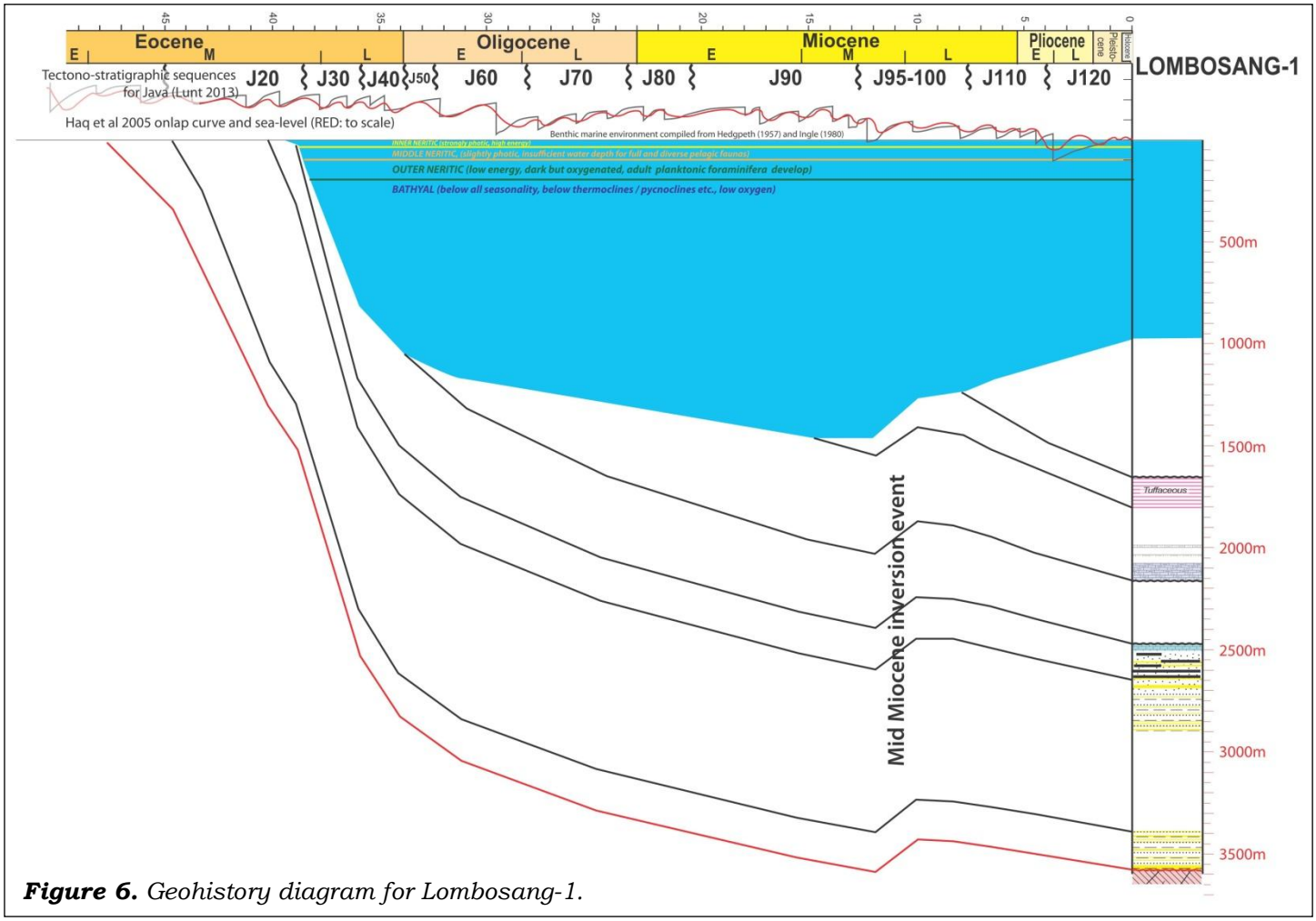


Figure 6. *Geohistory diagram for Lombosang-1.*

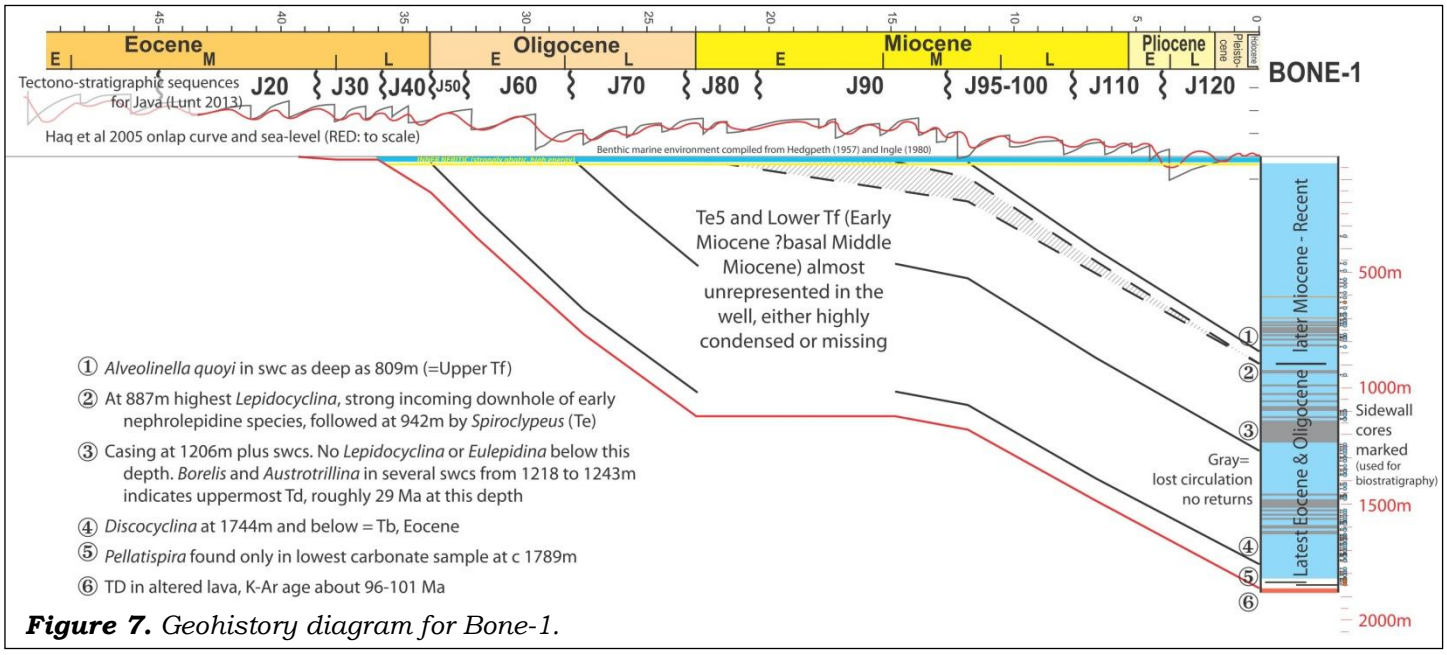


Figure 7. *Geohistory diagram for Bone-1.*

The nearby wells L-46-1 & -2, ST Z-1 and SG P-1 also seem to have a later Middle Eocene subsidence and larger intra-Late Eocene subsidence to fully bathyal conditions. To the southeast the Lombosang-1, SSA-1, Soreang-1, Tanakeke-1, Kelara-1 and ODB-1 wells all show a marked and sudden subsidence to deep marine conditions within the Middle Eocene (intra P14 or P13) and this tectonic event is a different (Spermonde) rift and not discussed here. Soreang-1, ODB-1, SSA-1 and Tanakeke-1 also show additional subsidence at 36 Ma, but this is not clearly expressed in microfaunas that were already in a deep marine setting.

In the centre of the south Makassar rift the Kris-1 (K-1 in Bacheller et al., 2011) also contains this sudden intra Late Eocene transgression. However about 16 kms from Kris-1 the data on the Sultan-1 (S-1) well (Bacheller et al., 2011) suggests no

significant subsidence in Late Eocene times (although it might have been the event that first led to limestone being deposited over basement there). The S-1 site seems to have had continual growth of a reef from some time in the later Eocene until the latest Oligocene (after the evolution of *Miogypsinoides* at c. 25 Ma), as was also happening in TT to the west and Doang-1 and Bone-1 to the south. Unlike these other carbonate platforms the S-1 site then subsided, near the end of the Oligocene, to bathyal conditions, terminating reef growth. The current depth of the Eocene-Oligocene reef in S-1 is just a few hundred metres shallower than the deepwater deposits of the same age in K-1 (the good pick of the Eocene-Oligocene boundary is about 300m lower in K-1). On this limited data it is suggested that K-1 and S-1 were offset by 300m due to intra-Late Eocene fault movement, and K-1 became the site of condensed deeper water sedimentation through the Oligocene while S-1 hosted a reef, then both sites underwent additional subsidence at the end of the Oligocene. As a result of this K-1 was only onlapped by bathyal clastics during Middle Miocene times, and the slightly higher structure, and also reef, at S-1 onlapped in Late Miocene times. A reef similar to the one at S-1 is still not covered by sediment, and stands up to 300m above the surrounding sea-floor, which is at about 2050m, some 35 kms north of S-1. This feature, called Snorkel in De Man et al. (2011) was sampled by dredge/piston core and a Late Oligocene Te4 biohermal carbonate fauna was found (van Gorsel and Helsing, in prep.).

THE TERMINAL EOCENE EVENT AND OLIGOCENE SEDIMENTATION

The geohistory method also reveals other important stratigraphic changes after the large 39 and 36 Ma subsidence events. As noted above and in Lunt (2013), the Eocene to Oligocene boundary across the southern Makassar area, from Spermonde in the SE to Kangean in the SW is characterised in deep marine sediments by a stepped reduction in gamma-log response (up-hole) at the same depth that the highest Eocene microfossils are first seen in cuttings (c. 34 Ma). The end of the Oligocene, close to the termination of the Berai Limestone and its deep marine equivalents, is dated as between 23 and 24 Ma, and is associated with several biostratigraphic datums in both carbonate and planktonic facies. This gives a reliable correlation for base and top Oligocene. The top Berai Limestone event (near top Oligocene) is a major boundary that, in seismic lines perpendicular to the one examined here, shows highly condensed sedimentation after the end Berai event and then large scale progradation of clastics down the West Makassar Graben, sourced from the west (Kupecz et al., 2013, Figure 18).

Using these two reliable correlation points (base and near-top Oligocene), of known ages, the geohistory analysis shows the 10-11 Ma of the Oligocene is represented by some 550m preserved in MS-1 or about 700m un-compacted at base Miocene times, which is equal to between 64 and 70m/Ma. This contrasts with about 2830m of compaction-corrected sediment between the base of the Oligocene and the onset of transgression some 4 Ma earlier, or about 710m/Ma: almost a ten-fold reduction in the rate of sedimentation. This ten-fold change is a maximum, as MS-1 was in a graben depocentre, while other locations such as P-1, over a palaeo-high with more condensed Eocene sedimentation, saw Oligocene rates of sedimentation reduce to about a quarter of what they were in the Eocene. This drop in sedimentation rate is clear on the geohistory diagrams.

The terminal Eocene event is extremely clear in the L-1 well in the Spermonde Graben where a sharp log break separates Late Eocene claystones from very highly condensed Early Oligocene hemipelagic chalks. The entire Oligocene is represented by less than 150m, but this is close to the top of the highest sample examined, and above this there is no detailed age breakdown. However the reduction in sedimentary rate is so severe that it stands out in spite of the lack of biostratigraphy (Figure 6). At about 1660m in the well a seismic event correlated to other wells, and the main inversion event of the Spermonde Graben, is known to be about mid Middle Miocene in age. It is only after this event that late Neogene uplift and erosion of Sulawesi Island introduces a new sediment source and the rate of sedimentation at the L-1 location becomes significant.

As noted above, it is hard to compare rates of sedimentation in the graben with those seen in Eocene and Oligocene carbonate platforms on the horst-ed highs as there was frequent loss of circulation while drilling these sections, and subsequently very poor samples. Only Bone-1 has sidewall core coverage enough to give a reliable stratigraphy. There is only minor correction for compaction in platform carbonates, compared to the mudstone sections in other wells, and basement subsidence until the unconformity/hiatus near top Oligocene is indicated to be just over 1100m in about 13 Ma, or about 85 m/Ma. The Oligocene section only is 950m in 11 Ma (also 85 m/Ma).

THE TERMINAL OLIGOCENE EVENT AND EVIDENCE FOR A MID-OLIGOCENE EVENT

Pireno et al. (2009) describe how the Ruby gas field (discovered by the MS-1 well) is trapped in a major carbonate debris flow facies that is associated with the termination of the long-lasting Berai Limestone. This debris flow travelled some 4 to 6 kms horizontally from the collapsed carbonate shelf edge. As noted above, the Berai Limestone is equivalent to about 11 Ma of condensed clastic sedimentation in the lows. Such large debris flows

are only seen at one other time in the underlying section, in about mid-Oligocene times (close to the extinction of *Nummulites* at about 28.2 Ma; Lunt & Allan, 2004). This is observed in MS-1, MS-3, and MS-4 wells (Pireno et al., 2009). The mid Oligocene debris flow does not appear to be as large (as thick or as widespread) as the terminal Berai slumps and flows. In addition the terminal Berai event is associated with a widespread change in lithofacies, while the mid-Oligocene event was succeeded by continuation of the same lithofacies. However they can both be interpreted as the products of large scale tectonic or eustatic changes.

Around the south Makassar region it has been noted that there are just two significant stratigraphic boundaries associated with Oligocene sedimentation, one in mid-Oligocene times and one virtually on the Oligo-Miocene boundary. Closest to the study area is the cluster of pinnacle reefs around S-1 (Bacheller et al., 2011) that were drowned out in very latest Oligocene times, and since then have subsided to a depth more than 3 kms below sea-level. While there was a temporary shift to clastic sedimentation above Te1-4 platform limestones at TT-2 and Berlian-1, those areas (c. 100 kms west of S-1) were again the site of biohermal carbonate growth soon afterwards, whereas the S-1 location was so deep it was not onlapped (by bathyal mudstones) until Late Miocene times. This suggests that at end of Oligocene times there were considerable differences in vertical movement between S-1 and TT-2 as well as Berlian-1 and also Doang-1 and Bone-1 (c. 190 kms & 230 kms to the south respectively). In these last two named sites carbonate platforms, growing near sea-level, continued from Oligocene and through the Miocene. It is this geographic variation in vertical displacement, relative to sea-level, that suggests a tectonic rather than a eustatic cause for the terminal Oligocene event in South Makassar. Similarly Lunt (2013) noted striking difference in vertical displacement in adjacent areas of the eastern Java Sea (around the NSA-1D well) in mid-Oligocene times, close to or just above the extinction of *Nummulites* at 28.2 Ma. For this reason a tectonic cause is favoured for both Oligocene times of stratigraphic change, but more data is required on the weaker mid-Oligocene event, mainly as intra Oligocene sections are hard to date accurately with biostratigraphy.

SUMMARY OF THE MAIN SEDIMENTARY SEQUENCES, EOCENE TO BASAL MIOCENE TIMES

Geohistory analysis indicates that there are 5 main sequences of sedimentation in the south Makassar Straits from Eocene to Early Miocene times, and that these sequences are separated by tectonic induced unconformities.

Within the Middle Eocene, or just a short while before it, rifting began on the south and southeast margin of Sundaland (the area now occupied by the Makassar Straits), with non-marine or paralic sedimentation slightly exceeding the rate of basement subsidence. At the same time lacustrine sediments were deposited in land-locked grabens in the more inland area around the West Makassar Graben.

At about 39 Ma (before the mass extinction of planktonic foraminifera at top P14) a tectonic event accelerated the rate of subsidence, particularly in grabens in the south and southeast. This led to the onset of very deep marine conditions in those areas. In the West Makassar Graben this event may have been the cause of the shallow marine transgression over the lacustrine deposits.

At 36 Ma (within the lower part of the late Eocene; about mid foraminiferal Zone P15), the main part of the southern Makassar Straits, including the West Makassar Graben, was subject to subsidence of an outstanding magnitude that can be measured using data from MS-1 (calibrated to P-1). This appears to be the event that created the south Makassar Straits as an open seaway. It completely changed basin architecture and sedimentation over a very wide area.

The fourth sedimentary phase was initiated by the severe drop in clastic sedimentary input on the Eocene to Oligocene boundary [34 Ma], which can be seen on geohistory plots from several wells. The mid-Oligocene event [roughly 28 Ma] produced a log-correlatable event near the extinction of *Nummulites* and *Chiloguembeina cubensis* (a small planktonic foraminifera not always recorded in older reports) in many wells, but it does not see a major shift in facies development. On the whole, the Late Oligocene in most areas did not receive significantly different sediments than the Early Oligocene.

The fifth major sedimentary sequence was the onset of renewed clastic sedimentation into the West Makassar Graben and other lows after the terminal Oligocene events. This early Miocene sediment was initially slow and distal, but rapidly prograded and filled, with sediment supply soon exceeding basement subsidence rate.

The importance of identifying these fundamental sequences is that Walther's Law of facies relationships will apply within these major units, but across the bounding unconformities these relationships, and any palaeogeographic predictability, breaks down. The magnitude of the lithofacies changes across these sequence boundaries, as well as the geographic variation in amount of contrast, suggests these first-order sequence boundaries were tectonic events.

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