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DISCUSSION

Gravity anomalies, subsidence history and the tectonic evolution of the Malay and Penyu Basins (offshore Peninsula Malaysia)

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To demonstrate the extensional origin of the Malay Basin and calculate the stretching factor (β), Madon & Watts (1998) conducted subsidence-history backstripping on more than 60 wells. The resulting backstripped basement depths through time were then matched to best-fit theoretical subsidence curves, suggesting a McKenzie (1978)-type basin with rapid extensional subsidence ('synrift') followed by slower thermal subsidence ('postrift'). However, the match is only 'relatively poor' (p. 381) for the first half of the basin's 35–0 Ma history (see subsidence curves, Madon & Watts, 1998, fig. 7). In the second half, the match looks better on cursory inspection of the subsidence curves, but this is partly an artefact of lacking basement-depth data points over part of this time interval (e.g. 19–0 Ma in well M-6; 7–0 Ma in all 12 illustrated wells). The 'data gap' reflects a late Miocene regional inversion event which separated the 'early postrift' and 'late postrift' stages. Although this inversion is mentioned in the text of Madon & Watts (1998; see also unconformity on their fig. 6), it is curiously ignored on their backstripped subsidence curves (fig. 7), which instead imply smooth, continuous thermal subsidence, a misleading impression considering that this 'massive regional uplift' (M. Ramli, 1988, p. 178) locally reached 'as much as 4000 feet' (Du Bois, 1985, p. 183) and produced many of the basin's petroleum traps (Ng, 1987). More realistically, the subsidence curves should show a sharp inflection and reversal at the time of inversion, with consequent steepening of the postinversion part of the curve.

The intentions of this discussion are three-fold: (1) to question this omission and to query whether the subsidence mechanism during the late postrift (postinversion) stage was partly extensional, rather than purely thermal as inferred by Madon & Watts (1998). The importance is that a better match would give more confidence in the subsidence-history model as a basis for future studies of petroleum prospectivity, such as modelling the timing of source-bed maturation and hydrocarbon migration relative to trap formation; (2) to point out some possible oversimplifications of the depositional environments assumed in the backstripping exercise (i.e. assumed palaeo-water depths), which might also partly explain the poor match between the backstripped and theoretical subsidence curves; and (3) to shed more light on the sedimentology of the Malay Basin, where despite three decades of oil and gas exploration, 'much of the geological and geophysical data remain unpublished' (Madon & Watts, 1998, p. 375).

DEPOSITIONAL ENVIRONMENTS AND PALAEO-WATER DEPTHS

Madon & Watts (1998) elected to ignore sea- or lake palaeo-water depths in their backstripping exercise, on the grounds that the basin was 'nonmarine' during much of its Oligocene to Recent history (p. 380). This *non sequitur* (nonmarine environments can include lakes hundreds of metres deep) also contradicts the authors' disclosure that the late postrift interval, of late Miocene to Recent age (p. 379) and thus representing as much as 15–30% of the basin's time span, is of shallow marine origin (p. 379), deposited in water possibly as deep as 200 m (p. 380). In addition, the literature suggests that much of the synrift and early postrift interval was deposited in at least tens of metres of water, rather than 'at or near sea level' (p. 379). For example, the synrift deposits are widely interpreted as offshore lacustrine in part (M. Ramli, 1988; Yakzan *et al.*, 1994; Madon & Watts, 1998), including oil and gas source beds (Creaney *et al.*, 1994; Cole & Crittenden, 1997; Todd *et al.*, 1997). According to Cole & Crittenden (1997), parts of the synrift and early postrift intervals are 'deep lake' deposits (tens to hundreds of metres water depth are implied by their fig. 10); these authors interpreted the postrift lakes as marine-connected, based on microfaunal evidence for brackish water (part-time brackish water was also mentioned by Madon & Watts (1998, p. 379)). On the other hand, many previous authors interpreted the early postrift interval as largely shallow marine (N. Ramli, 1986, 1988; M. Ramli, 1988; Ibrahim & Madon, 1990). According to M. Ramli (1988), the entire postrift succession in the SE Malay Basin axial region is marine, including his 'coastal fluviomarine' belt, a microfaunally defined tract whose position and width on palaeofacies maps (Ho, 1978; M. Ramli, 1988, figs 8 and 22–29) indicate correspondence to the delta front and innermost shelf in sedimentological terminology. Based on Ramli's maps (figs 22–29), the Malay Basin was a NW-narrowing marine gulf throughout postrift time, a geometry predisposed to strong tidal currents (Johnson & Baldwin, 1996). Some of the supposed marine-connected lakes of Cole & Crittenden (1997) could instead be marine, consistent with these authors' report of benthonic foraminifera and (unspecified) evidence for tidal currents (their fig. 14). Planktonic foraminifera are rare in the early postrift section (Armitage & Viotti, 1977), as on many clastic shelves (e.g. Emery & Myers, 1996, p. 93 and fig. 6.2), possibly due to high turbidity (suspended clay) or reduced salinity, both attributable to tropical river inflow into a narrow marine 'Malay gulf'. This 'turbidity effect' of restricting planktonics on the shelf is only slowly becoming appreciated. Previously, the scarcity of planktonics in the early postrift section led Armitage & Viotti (1977) erroneously to invoke deposition on a coastal plain, despite relatively diverse benthonic foraminiferal faunas and locally abundant glauconite (Trengganu Group and Bekok Formations). In contrast, planktonics are diverse and abundant in the late-postrift Pilong Formation, reflecting postinversion widening of the Malay gulf to its present form (Gulf of Thailand), such that the central offshore region was far enough from terrestrial mud input for 'clearwater' planktonic foraminifera to thrive.

Allochthonous coal beds

Coal beds are common in both the early and late postrift intervals. The coals led Madon & Watts (1998) to assume that deposition occurred in a nonmarine environment 'at or near sea level' (p. 379), implying a coastal- or delta plain of basinwide extent. However, aside from the implausibility of a delta plain more than twice as long as any modern example (e.g. 300 km in Leo, 1997, fig. 2; 500 km+ in Worden *et al.*, 1997, fig. 1), a common, unpublished opinion among oil-company geologists is that many of these coal beds are allochthonous, implying deposition offshore in a lake or sea. (True *in situ* coastal-plain coals probably do exist toward the basin margins, given the humid tropical palaeoclimate (Cole & Crittenden, 1997) and the postrift tectonic setting, i.e. nonfaulted basin margins suitable for low-gradient coastal plains.) Published evidence for Malay Basin coals being allochthonous is confined to the base and top of the postrift succession. Near the base, in the 'J' seismic unit (Madon & Watts, 1998, fig. 6), thin (<0.6 m) coal beds lack roots and were interpreted by N. Ramli (1986) as storm-transported plant material deposited on a marine shelf. Near the top, the late-postrift Pilong Formation (Pliocene to Recent; seismic units 'A' and 'B') is mainly foraminiferal mudstone, interpreted by Armitage & Viotti (1977) as shallow marine deposits, despite the presence of 'thin beds of black lignite' (p. 75). Many more coal beds occur in the intervening 'D' to 'I' units, including the informal 'Sand-Coal Formation' (N. Ramli, 1986, fig. 2), but detailed published sedimentological descriptions are lacking. Lawrence *et al.* (1998) interpreted coal beds in the early postrift interval in the NW part of the basin as fluvial and deltaic, but without mentioning whether roots were observed.

Elsewhere in the world, published records of offshore marine or lacustrine allochthonous coals are few. In the modern Catatumbo delta of Lake Maracaibo, plants eroded from distributary banks by floodwaters are deposited on the delta front as peat layers up to 2 m thick (Hyne *et al.*, 1979), to form future discontinuous allochthonous coal beds. Thompson *et al.* (1985) postulated that inner-shelf facies in SE Asia (Recent) and Norway (Triassic–Jurassic) might contain 'drift peats' and 'drift coals', respectively. Cabrera & Saez (1987) interpreted coal beds in the Oligocene of Spain as allochthonous, offshore–lacustrine deposits. In the Coal Measures of England, duplicated coal seams are attributed to rafting of peat mats during floods, but with only short-distance transport, within the delta plain (Elliott, 1985).

Similar rafting of tropical, coastal-plain peats to that described by Elliott (1985), but over larger distances (10s km rather than 10s–100s m?), could have carried peat mats eroded from the delta plain into offshore waters of the postulated Malay gulf following catastrophic flooding events such as hurricanes (typhoons) or tsunamis. Subsequent 'herding' of the peat rafts and other drifted vegetation into the gulf apex or into an embayment or gulf bottleneck by tidal or wind currents prior to sinking could have formed a 'peat-and-log jam', resulting in a laterally extensive allochthonous coal bed.

The apparent rarity of allochthonous coal beds in shelf deposits of other basins suggests either that special conditions existed in the Malay Basin or that allochthonous coals have been widely misinterpreted as autochthonous in the literature. A possible prerequisite was a tsunami generator facing into the Malay gulf, for which a candidate is the NW Borneo Trough to the SE (for location, see Madon & Watts, 1998, fig. 1, Sabah and Sarawak Basins). The Borneo Trough was a subduction-related deep-sea trench in the Eocene–Miocene, evolving into a Miocene to present deep-sea (3000 m) foreland-basin trough (Rangin *et al.*, 1990; Sandal, 1996; see especially plate-tectonic reconstructions of Hall, 1997, fig. 5). Slumps and slides have occurred on the steep inner (SE) slope of the trough throughout Middle Miocene to Quaternary time (Levell & Kasumajaya, 1985; Casson *et al.*, 1998); they could have generated tsunamis analogous to Quaternary cases in Europe and Hawaii (Dawson *et al.*, 1988; Young & Bryant, 1992; Moore *et al.*, 1994). A potential tsunami threat is implied for the modern Gulf of Thailand, and should be taken into consideration in the design of offshore and coastal hydrocarbon-production infrastructure.

In summary, the assumption by Madon & Watts (1998) that the Malay Basin coals are *in situ* and therefore imply coastal-plain or delta-plain deposition is questionable, based on the above evidence that much of the Malay Basin fill was deposited offshore in lakes and seas, and the suspicion that most coals are transported. The interpretation preferred here is that the coals are mostly allochthonous beds, deposited offshore on a shelf (gulf). The coal beds and impoverished microfaunas continue to mask the offshore marine origin of the early postrift succession and to mislead geologists into marginal-marine interpretations such as coastal plain, delta plain, estuarine, intertidal flat, lagoonal and paralic (Creaney *et al.*, 1994; Elias & Dharmarajan, 1994; Lovell *et al.*, 1994; Yakzan *et al.*, 1994; Lawrence *et al.*, 1998). Crucially for petroleum exploration and production, the two alternative models predict different sand reservoir geometries (e.g. tidal shelf sand sheets and/or ridges vs. deltaic channels). For example, in the Bongkot Field near the NW end of Malay Basin, the early postrift interval (main gas pay) contains coal beds and poor microfaunas (Du Bois, 1985, fig. 7), prompting a delta-plain interpretation with mainly channel reservoirs (Duval & Gouadain, 1994; Leo, 1997). However, a marine gulf with allochthonous coal beds is a possible alternative interpretation (pending publication of whether the coal beds have roots or seatearths), and could imply larger gas reserves due to the greater predicted areal extent of the reservoir sands.

WATER-DEPTH FLUCTUATIONS

In the judgement of Madon & Watts (1998), 'The abundance of coal in the postrift succession suggests that the basin … was influenced by only minor fluctuations in sea level' (p. 379), another *non sequitur*. On the contrary, (glacio-) eustasy has been rampant since the Oligocene, with global sea-level oscillations possibly exceeding 100 m (Haq *et al.*, 1988, fig. 14), which would inevitably have been felt in the Malay Basin, whether it was a delta plain or a marine gulf, producing incised valleys on the coastal plain and/or on the drained gulf floor during eustatic lows. Eustatic oscillations would also have been felt in sea-connected lakes (see above), whenever eustatic sea level was high enough to overtop the lake sill.

'LATE POSTRIFT' THERMAL SUBSIDENCE OR RENEWED RIFTING?

It seems likely that the 'late postrift' interval, attributed by Madon & Watts (1998) to pure thermal subsidence, actually includes an element of postinversion extension. Lending support to this suggestion, Ng (1987, p. 181) mentioned a 'minor extensional tectonic phase' in the Pliocene. According to Waples *et al.* (1994), the proposed second extension, beginning in Pliocene time and still in progress, was 'much stronger' than the first; this could account for the late postrift (postinversion) Pilong Formation being 'more marine' than the early postrift deposits (see above), reflecting rapid subsidence due to the second extension, resulting in a wider and deeper Malay gulf than before, despite lower average eustatic sea levels in the Plio-Quaternary than in the Miocene (Haq *et al.*, 1988). Also supporting a second extension, Todd *et al.* (1997, p. 26) referred to postinversion 'collapse' of this and other SE Asian basins, from late Miocene time until the present. Young extension, possibly still in progress, is suggested by faults (latest sense normal) which reach up into the Pliocene and almost to the sea floor on seismic line drawings of Madon (1997a, fig. 6) and Madon & Watts (1998, fig. 6) (see also cross-sections in Hutchison, 1996, fig. 3.14A,B). These basement faults are possibly double-reactivated, i.e. 'first-rift' normal faults, reversed during the inversion, then reverting to ('second-rift') normal faults. Abnormally high heat flow in the Malay Basin (Abdul Halim, 1994) is consistent with ongoing extension, and is considered by Waples *et al.* (1994) to have begun at the onset of the *second* extension, at about 5.5 Ma.

CONCLUSION

Would Drs Madon and Watts care to discuss the extent to which the relatively poor match between their backstripped and calculated subsidence curves might be improved if water depths are taken into account? Would the basin be better modelled as having *two* subsidence episodes, each involving extensional crustal thinning, separated by an episode of compression or transpression? Would the incorporation of water depths and/or an element of young extension in the model improve the only 'relatively good' correlation between the observed heat flows and those predicted from the backstrip-derived values (p. 381 and fig. 8B)?

REPLY

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Higgs comments on Madon & Watts (1998) are primarily concerned with two aspects of our analysis: (1) whether palaeobathymetry has any effect on the backstripping results and (2) whether the Malay Basin would be better modelled as having undergone two, instead of one, episode of rifting. We shall discuss these two issues in turn below.

PALAEOBATHYMETRY

As is well known in backstripping studies, an error in the palaeobathymetry translates directly as an error in the total tectonic subsidence (TTS). In our analysis we assumed that the palaeobathymetry during much of the basin history was less than 200 m, based on the unpublished micropalaeontological studies, summarized by Yakzan *et al.* (1994). Higgs' objections to this 'oversimplification' hinge on the interpretation of the depositional environments in the basin. We think that a detailed discussion of depositional environments was beyond the scope of our paper. Nevertheless, the depositional environments of the basin have been well established and described by previous authors, including those cited by Higgs. The lack of age-diagnostic microfossils in most parts of the sedimentary succession, and especially in the synrift succession, however, has prevented a more accurate age determination. We have relied on the latest ages determined by Yakzan *et al.* (1994) in our analysis. Our palaeoenvironmental interpretations were based on sedimentological studies done on some parts of the succession by previous authors. The synrift (groups M to K) deposits comprise those of braided streams, fan deltas, lakeshore and offshore lacustrine (M. Ramli, 1988; N. Ramli, 1988; Lovell *et al.*, 1994). Although the synrift succession and some early postrift may contain lacustrine deposits that could have been deposited in 'deep lakes', we have no way of determining palaeo-water depths. 'Deep' can be anything from tens of metres to a few thousand metres. Stratigraphic data from the synrift section in the basin centre is generally not available because of lack of penetration.

Figure 1 shows the subsidence curve from well M-7, which is located on the SW margin of the basin. Here, we have some stratigraphic data from the top of the synrift section. For this reply, we assumed a palaeowater depth of 1.5 km for the deep lake during group M time. The figure shows a large uncertainty in the synrift subsidence but less in the postrift. As pointed out in Madon & Watts (1998), the large misfit between the observed and theoretical subsidence curves betwen 35 and 15 Ma could be due to rift-flank uplift arising from lateral heat flow effects. For comparison, Fig. 2 shows the subsidence curve calculated for well M-5 of Madon & Watts (1998) which is located in the central part of the basin, where lateral heat effects may have been insignificant. As shown in this figure, a palaeobathymetry uncertainty of ±200 m makes little difference to the tectonic subsidence, and a single rifting event could explain the subsidence history quite well.

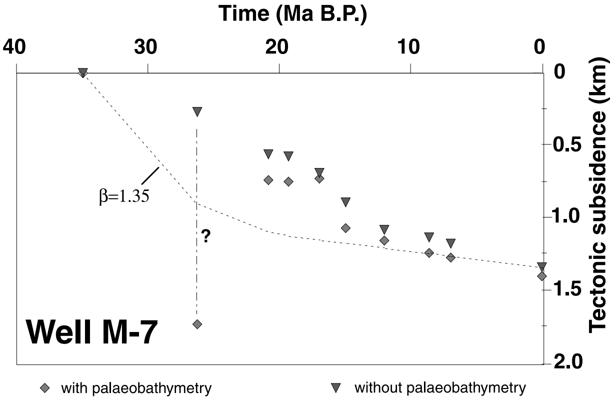

Fig. 1. Tectonic subsidence history at well M-7, on the south-western margin of the Malay Basin (in Madon & Watts, 1998, fig. 7) showing the effect of palaeobathymetry. Note the large uncertainty in the synrift subsidence due to lack of data. For this calculation, a 1.5-km lake was assumed at 26 Ma. Note that an error in palaeobathymetry translates directly to an error in tectonic subsidence. A theoretical subsidence curve for $\beta = 1.35$ is included for comparison.

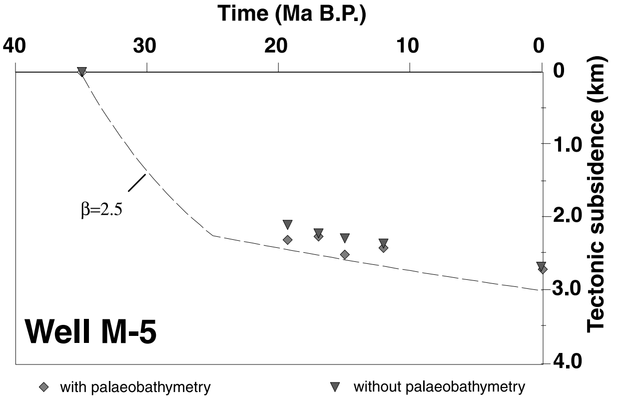

Fig. 2. Tectonic subsidence history for the central part of the Malay Basin, based on data from well M-5 (in Madon & Watts, 1998, fig. 7) showing the effect of palaeobathymetry. Note the lack of stratigraphic data for ages less than 20 Ma. However, a maximum palaeowater depth of 200 m has been assumed for the J group (age 20.9 Ma) to see the error involved. The dashed curve shows the theoretical water-loaded subsidence for a β factor of 2.5.

In contrast to the Oligocene synrift section, the overlying Miocene–Pliocene seismic groups are generally marine-influenced coastal plain and subtidal shallow-marine deposits (Lovell *et al.*, 1994). The lower Miocene Groups J and I are fluvial to tidally dominated estuarine deposits with interbedded coals, especially in the I group. As noted by Madon & Watts (1998, p. 380), the late postrift interval (late Miocene to Pliocene) comprises alternating shallow-marine, fluvial/estuarine and coastal plain deposits. Regional palaeoennvironmental studies based on foraminiferal assemblages (Yakzan *et al.*, 1994) showed that the marine deposits represent shallow water (inner to middle neritic) of not greater than 100 m. Even so, the middle neritic deposits were recorded only in the south-easternmost part of the basin. Hence, it is reasonable to assume that the palaeobathymetry during the postrift phase never exceeded 200 m (Madon & Watts, 1998, p. 380). This range of possible palaeowater depth simply translates into an error in the tectonic subsidence (Figs 1 and 2).

Higgs disagreement on our assumption of the palaeobathymetry hinges upon his assertion that the coals in the early postrift section are allochthonous, citing some examples from other parts of the world. Based on many studies, including unpublished work by oil companies, we do not believe that most coals in the postrift section of the Malay Basin are allochthonous in origin. The 0.6-m-thick 'coal bands' mentioned by N. Ramli (1986) in the basal J group are probably made up of transported plant material, but do not necessarily represent the entire postrift section from groups J to A. Higgs' suspicion that most coals in the Malay Basin are transported is not supported by data. Sedimentological descriptions of groups I to D have been published (Khandwala *et al.*, 1984; Thambydurai *et al.*, 1988; Madon, 1994). All these studies reported coastal plain deposits with abundant *in situ* coals deposited in fluvial–deltaic environments. A detailed study of the group E sandstones by Madon (1994) includes a description of coal beds with root casts at the top of fining-upward fluvial parasequences.

ONE OR TWO RIFTING EPISODES?

Higgs speculated that the late postrift interval (seismic groups A and B) is the result of renewed rifting during the late Miocene rather than due to thermal subsidence. He cited Ng (1987) who mentioned a 'minor extensional tectonic phase' in the Pliocene which resulted in the formation of younger normal faults which cut major east–west anticlines. These north–south trending normal faults, however, are generally detached from the basement, and therefore are not due to crustal extension. Instead, they were formed by right-lateral wrench motion that produced the compressional anticlines during basin inversion (Tjia, 1994; Madon, 1997a). A 'second extension' event in Pliocene times was invoked by Waples *et al.* (1994) as a possible explanation for the apparently anomalous vitrinite reflectance (R_o) data in some wells in the basin. In that same paper, Waples *et al.* (1994) also showed that equivalent R_o data measured using the technique called flourescent alteration of multiple macerals (FAMM) were higher than conventionally measured R_o, suggesting that there could be suppression of vitrinite reflectance. They further showed that the thermal history of the basin can be modelled using a single extension event if the measured R_o data were corrected for the suppression. In fact, in our modelling (the details in Madon, 1997b) we have used the same corrected R_o dataset obtained from Waples *et al.* (1994). Hence, we believe that a single extension episode is valid for the Malay Basin (Fig. 2).

Basin inversion began at about 7 Ma (middle Miocene) and corresponds roughly with the base of seismic group H. Since the inversion was caused by tranpressional shear of the Malay Basin axial fault zone (Tjia, 1994; Madon, 1997a), the effect of the basin inversion was not uplift of the entire basin, but compressional deformation and re-adjustment of the basement faults that resulted in localized folding of the sedimentary infill. This deformation took place while the basin was still undergoing thermal subsidence related to the Oligocene extension. It should be noted that most of our data points for the subsidence analysis (Madon & Watts, 1998, fig. 8A) are located on the basin margins which are less affected by the compressional deformation. At most of these locations, the amount of erosion due to inversion is insignificant. We would like to point out though that abundant and diverse planktonics in the late postrift section, as noted by Higgs, does not necessarily reflect widening of the basin due to extension, but may simply be a response to sagging due to thermal subsidence.

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