PALAEOGEOGRAPHY 3

AUSTRALIA

AUSTRALIAN SEALEVEL CURVES

PART 1: AUSTRALIAN INUNDATION CURVES

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by

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Phanerozoic History of Australia Project

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ABSTRACT

Measurement of areas of marine flooding from 70 palaeogeographic maps produced during the BMR-APIRA Palaeogeographic Maps Project has provided a first order inundation curve for the Australian Phanerozoic. The most extensive flooding of Australia took place in the early mid-Cambrian and the Early Cretaceous with further highstands occurring in the Early Ordovician, Late Devonian, Early Permian, Late Jurassic, Eocene, Early Miocene and Pliocene. Some transgressions and regressions depicted on the Australian inundation curve correlate with events shown on published sealevel curves and may reflect eustatic events. But in some instances, considerable differences are present; for example the Late Ordovician regression, the Early Permian highstand and the Aptian highstand of the Australian curve are not recognizable on published curves.

Marine flooding curves for individual Australian basins were also produced. Their shape depends very strongly on the tectonic setting of the basin during a particular time, indicating that, in many cases, local and regional tectonic events dominate the Australia-wide curve. This probably also applies to published curves which would also contain regional bias.

The occurrence of known hydrocarbon source rocks throughout the Australian Phanerozoic indicates that they accumulated preferentially during relative sealevel highstands. Important reservoir facies developed during both lowstands and highstands of relative sealevel, and the type and geometry of sandstone reservoirs was also influenced by sealevel. Depositional environments in intracratonic basins, and thus the occurrence of source and reservoir rocks, were also partly controlled by relative sealevel. The basin flooding curves are most useful for the assessment of the distribution of source and reservoir facies and their relation to sealevel changes, as they closely reflect the effects of sealevel, sediment supply and tectonic activity in a particular basin; the Australian inundation curve shows the general trend of movements of the coastline with time in a wider, regional context.

1. INTRODUCTION

The construction of Australian sealevel curves is part of the program of the Phanerozoic History of Australia Project; it is planned to be completed in two stages. Stage I draws on the data base acquired during the BMR-APIRA Palaeogeographic Maps Project by using palaeogeographic maps for 70 time slices from the Cambrian to Recent for the construction of an Australian inundation curve and inundation curves for selected basins. Comparison of these curves with published sealevel curves and an assessment of the effect of relative sealevel on depositional environments in non-marine basins are further products of Stage I.

For Stage II, it is planned to construct coastal onlap curves for selected areas using seismic stratigraphic methods. It is planned that in conjunction with subsidence curves for these areas and comparisons with the inundation curves of Stage I as well as published sealevel curves, the effects of local tectonics and epeirogenic movements can be estimated.

This report draws together the results of Stage I of the Sealevel Project including a brief literature review on the causes of eustatic sealevel changes, methods for estimating sealevel changes and some of the problems involved. The concluding section details the implications for resource exploration.

2. THE CONCEPT OF GLOBAL SEALEVEL CHANGES

Since Suess (1906) introduced the term 'eustatic' for global changes of sealevel, a wealth of papers dealing with the recognition of sealevel changes from the sedimentary record, their global correlation and the mechanisms involved, has been published (e.g. Fairbridge, 1961; Hays & Pitman, 1973; Vail & others, 1977a, b; Hallam, 1984; Haq & others, 1987). Only a few of these contributions can be considered in this report.

There is now general agreement that movements of the shoreline with time are the result of the combined effects of eustasy, local or regional tectonic movements, and sediment supply. Thus, the sedimentary record provides information on apparent changes of sealevel with respect to the land surface. It appears reasonable to assume that elimination of the effects of sedimentation and local or regional tectonic signals from relative sealevel curves should produce a record of eustatic signals through time. Many attempts have been made to explore the relationship between the various parameters and to quantify the effects of sediment compaction, loading and thermo-tectonic history of sedimentary sequences in order to isolate the eustatic signal (e.g. Bond, 1978; Hardenbol & others, 1981; Watts, 1982; Hallam, 1984; Guidish & others, 1984; Burton & others, 1987); some of these will be discussed briefly later in this section.

2.1 EUSTASY

The most commonly cited causes of eustatic sealevel changes are (a) changes in the volume of ocean water, and (b) changes in the volume of ocean basins.

Changes in the volume of ocean water

Mechanisms causing a change in the volume of ocean water include the melting and freezing of polar ice caps (glacio-eustasy), mountain glaciations, variations in oceanic temperature and atmospheric moisture content, and desiccation or flooding of ocean basins. Of these, the melting and freezing of ice caps can cause sealevel changes of up to 200m at fast rates over a time interval of approximately 0.1 Ma (Pitman, 1978), whereas mountain glaciations generally have a negligible effect on sealevel. Donovan & Jones (1979) suggested that the desiccation of the Mediterranean in the Late Miocene (Hsü & others, 1973) caused a sealevel rise of approximately 12m and that a rise of 10°C in mean oceanic temperature could cause a sealevel rise of approximately the same magnitude. Sealevel changes resulting from variations in atmospheric moisture content are probably negligible (Donovan & Jones, 1979).

Changes in the volume of ocean basins

Variations in the volume of oceanic ridges resulting from changes in spreading rates, varying lengths of spreading axes, creation of new ridges or subduction of old ridges cause changes in the volume of ocean basins and thus eustasy fluctuations (tectono-eustasy) (Hallam, 1971;

1984). Pitman (1978) suggested that this mechanism can cause eustatic sealevel changes of up to 500m at slow rates over a time interval of about 70 Ma. Reductions in the volume of ocean basins due to sedimentation are mostly offset by subsidence due to sediment loading as well as removal of sediments at subduction zones. Crustal shortening through orogenies can result in a low rate sealevel fall of up to 100m over a time interval of about 70 Ma, whereas creation of new lithosphere over hot spots can cause a sealevel rise of the same magnitude at the same rate (Pitman, 1978).

Thus, there are a number of mechanisms that can cause eustatic sealevel changes, but most authors agree that only melting and freezing of ice caps and changes in ridge volume are of major importance. It is generally accepted that long-term changes (300 to 10 Ma) of sealevel (1st and 2nd order oscillations of Vail & others, 1977b) are due to tectono-eustasy (Pitman, 1978; Hallam, 1984). Some or most of the 2nd and 3rd order rapid falls in the Ordovician, Permo-Carboniferous and late Cainozoic are believed to be related to glacio-eustasy, but for the majority of short-term fluctuations no convincing mechanism has yet been put forward and they remain controversial. Some alternative explanations have been proposed. For example, Mörner (1976, 1980) suggested that rapid sealevel changes may be caused by changes in the geoid surface (geoidal-eustasy) and that these changes may result in diachronous sealevel changes in different parts of the Earth. However, Christie-Blick & others (in press) pointed out that geoidal changes are not relevant for sealevel fluctuations over time intervals longer than thousands of years.

Cloetingh & others (1985) and Karner (1986) argued that variations in intraplate stress fields may cause vertical movements of the Earth's surface resulting in relative sealevel fluctuations of about 1cm/1000 years corresponding to the 3rd order cycles proposed by Vail & others (1977b). Apart from horizontal plate movements, epeirogenic motion of continents or parts of continents may provide a mechanism for short-term variations of relative sealevel. However, very little is known about the ultimate cause of such broad scale uplifts of continental areas, although various models have been presented. A discussion of the different models is beyond the scope of this study, but there appears to be some agreement among authors that epeirogeny is caused by chemical processes or mass transfers in the mantle. Reviews of the various models were given by McGetchin & others (1980) and Sahagian (1987). Davies (1988) suggested that large scale mantle superswells involving lateral temperature variations may cause lithospheric stretching and rifting and resultant vertical movements of continental lithosphere of up to one kilometre.

2.2 METHODS

A variety of methods has been proposed for estimating changes of sealevel with geologic time. They include palaeobathymetry estimations (e.g. Bandy, 1953; Tipsword & others, 1966), calculation of varying areas of marine flooding of continents (e.g. Hallam, 1984), correlation of unconformities from seismic sections and outcrops (Vail & others, 1977a) and calculation of ridge crest volume through time (Hays & Pitman, 1973; Pitman, 1978). Not all of these procedures can be considered in this study, but some of the more important methods are summarized in the following paragraphs.

Continental Flooding

The continental flooding method involves measurement of continental areas covered by marine sediments for any particular time interval (e.g. Hallam, 1984). Using a planimeter and an equal area projection, these areas can be derived from a set of palaeogeographic maps. A plot of the areas in relation to the present-day land-sea distribution provides a record of marine inundations of continents through geologic time. The accuracy of the method is dependent on the reliability of data used for the production of the palaeogeographic maps and the length of the time slices used, i.e. the area of flooding increases with increasing length of the time slice because all marine sediments occurring within this time interval are included. A further factor which affects the accuracy of the method is the use of non-palinspastic maps. The curves obtained using this method provide a record of the combined effects of eustasy, tectonic subsidence and sedimentation rates and therefore give a relative sealevel curve.

The continental flooding method can be used in conjunction with hypsometric data to estimate the magnitude of relative sealevel changes. A hypsometric curve describes the area/height distribution over a given area, such as a sedimentary basin or a continent. Based on the theory that continents undergo slow vertical motions of up to several hundred meters (Menard, 1973), a number of authors (e.g. Eyged, 1956; Forney, 1975; Bond, 1978; Harrison & others, 1981; Cogley, 1981, 1985; Hallam, 1984; Wyatt, 1984) used present-day hypsometric curves for various continents in an attempt to calculate the magnitude of sealevel change needed to inundate given areas of these continents. Harrison & others (1981) pointed out that the hypsometry of a continent is not constant because of changes in ridge crest volumes, orogenies, plate-tectonic configurations, and sedimentation rates; this results in changes in continental area and average elevation. They calculated hypsometric curves for selected Phanerozoic periods using plate tectonic reconstructions in an attempt to reduce the error. Burton & others (1987) recommended the use of hypsometric curves as a basis for estimating magnitudes of relative sealevel changes through the Phanerozoic, but they doubted that this method provides a record of true eustatic fluctuations.

Seismic and sequence stratigraphy

Assessment of sealevel changes using sequence stratigraphic methods involves the determination, from seismic cross-sections and outcrops, of the landward onlap of coastal deposits in unconformity-bounded depositional sequences (Vail & others, 1977a). Subsurface and outcrop data and a regional grid of seismic cross-sections which show a complete record of coastal onlap in the region are required to identify ages, sequence boundaries and other stratal patterns such as onlap, toplap and truncations. Construction of a chronostratigraphic correlation chart provides a record of cycles of relative rise, stillstand and fall of sealevel. The magnitude of a relative sealevel rise is estimated by measuring either the vertical component (coastal aggradation) or the horizontal component (coastal encroachment) of the progressive landward onlap of coastal deposits within a maritime sedimentary sequence. Calculation of the magnitude of a relative sealevel fall is carried out by measuring the difference in elevation between the highest coastal onlap in a given sequence and the lowest coastal onlap in the overlying sequence. This procedure is problematic because of possible erosion and differential subsidence during a sealevel fall. It also requires knowledge of the palaeobathymetry. The measured changes in sealevel are plotted against geologic time to produce a regional onlap/offlap curve and hence, a relative sealevel curve. Vail & others (1977b) produced a 'global onlap curve' by comparing and combining results from various sedimentary basins of mostly the northern hemisphere Atlantic region. They calibrated this curve against Pitman's (1978) sealevel curve which was derived from calculations of changes in ridge crest volume during the Cretaceous to Recent. Vail & others (1977b) contended that the resulting curve reflects eustatic changes of sealevel. The curve depicts three orders of cycles characterized by rapid falls and slow rises. The cycles have durations of 200 to 300 Ma (1st order), 10 to 80 Ma (2nd order) and 1 to 10 Ma (3rd order). In subsequent publications (e.g. Vail & Todd, 1981; Vail & others, 1984; Haq & others, 1987), the original eustatic curve was referred to as a chart of relative change of coastal onlap but was used as a basis for the construction of a smoother 'eustatic' curve. A great number of papers have been published since the Vail team first introduced the use of seismic stratigraphy for assessing sealevel fluctuations, and the method has been used and amended by geologists worldwide. One of the major problems in applying the method is the biostratigraphic correlation of sequences on a worldwide basis. Many authors also suggested that the Vail sealevel curves do not show true eustatic events but depict a product of tectonic movement and eustasy (e.g. Watts, 1982; Parkinson & Summerhayes, 1985; Miall, 1986). In an extensive review of the method, Christie-Blick & others (in press) concluded that magnitudes of eustatic events cannot be obtained from sequence stratigraphy alone because coastal aggradation results primarily from basin subsidence, not sealevel rise; also, downward shifts in onlap reflect the rate of sealevel fall relative to the rate of basin subsidence, not the magnitude of sealevel fall. The authors recommended a re-evaluation of the ages of sequence boundaries in order to re-assess the global synchroneity concept, whereas Hubbard (1988) suggested that the concept be discarded altogether and that each basin be regarded as unique in its history.

Geohistory analysis

Hardenbol & others (1981) used seismic stratigraphy and biostratigraphy in conjunction with subsidence history to quantify eustatic sealevel changes. The magnitude of long-term sealevel changes was calculated by measuring the distance between a crustal subsidence curve for a given location (after van Hinte, 1978) and the theoretical thermo-tectonic subsidence curve for that location (after Royden & others, 1980). Basement subsidence curves were obtained using palaeobathymetry as the datum and removing the effects of sediment compaction and sediment loading. Limitations of this method include uncertainties in estimating palaeobathymetry, problems in determining the compaction history of sediments and isostatic response to sediment loading as well as the choice of a thermo-tectonic model. Burton & others (1987) argued that at least "two of the three processes, sediment accumulation, eustasy, and tectonic subsidence, must be specified in order to determine the third". They concluded that only the sum of eustasy and basin motion can be determined but not the size of eustasy excursions alone.

Palaeobathymetry

Palaeobathymetric markers such as sedimentary structures and fossil indicators can be used to estimate water depth and hence, relative sealevel changes. A number of authors (Bandy, 1953; Tipsword & others, 1966) studied the present-day distribution of marine organisms, especially foraminifera, to estimate palaeo-water depths. Hardenbol & others (1981) argued that the accuracy of the method is acceptable for water depths of up to 200m.

Oxygen isotopic ratios

Changes in seawater chemistry due to glaciations are recorded in trace elements and isotopic composition of minerals in marine sediments and organisms, e.g. $^{18}O/^{16}O$ ratios increase when ice caps form due to the preferential transfer of lighter oxygen isotopes to the ice through evaporation and precipitation. Variations in oxygen isotopic ratios (δO^{18}) therefore reflect sealevel changes due to glaciations (e.g. Shackleton & Opdyke, 1973; Moore, 1982; Matthews, 1984). Burton & others (1987) suggested that the best approximation of relative, i.e. tectono-eustatic, sealevel changes can be reached by using a combination of coastal aggradation measurements dimensioned against oxygen isotope signals.

2.3 SUMMARY

Eustasy fluctuations are caused by worldwide changes in the volume of ocean water and the volume of ocean basins. Many attempts have been made to determine the timing and size of these excursions from the stratigraphic record. Methods to estimate sealevel changes include calculation of changes in ridge crest volume, measurement of continental areas covered by marine sediments through time with or without the use of hypsometric curves, measurement of coastal aggradation or encroachment using seismic-stratigraphic methods, divergence of crustal subsidence curves from thermo-tectonic model curves. Evaluation of these methods suggests that, to date, it is possible to obtain only the sum of eustatic sealevel, sedimentary accumulation and tectonic movement of the basement, although quantification of the variables is possible to a certain extent. Best approximations of eustasy excursions can probably be reached using a combination of two or more methods.

3. PHANEROZOIC INUNDATION CURVE FOR AUSTRALIA

3.1 DATA BASE

The data base used for the construction of Australian inundation curves comprises the 70 palaeogeographic maps produced during the duration of the BMR-AMIRA Palaeogeographic Maps Project (1984-1987). The time slices cover the entire Phanerozoic of Australia and, where possible, were chosen to coincide with major breaks in sedimentation; boundaries between time slices may therefore be an expression of geological events such as sealevel changes or tectonic movements. The length and number of the time slices for each period varies corresponding to the geological complexity of each period and the biostratigraphic control available. The maps depict a two-dimensional view of the palaeoenvironment distribution for each time slice. The environments were mapped in three categories, land, coastal and sea, with each category being further subdivided giving a total of 17 possible environments. The total area mapped for each time slice was dependent on the availability of data.

3.2 METHOD

For the construction of an Australian inundation curve the total area mapped for each time slice was measured and then adjusted to a common reference area, because the areas mapped differ for each time slice, thus introducing a variable error to the curve. The largest area mapped was chosen as reference area ($12,62 \times 10^6$ km^2 [Jurassic 9] for the Mesozoic to Cainozoic; $11,16 \times 10^6$ km^2 [Devonian 9] for the Palaeozoic). A change of scale at the Palaeozoic/Mesozoic boundary was implemented because the difference between the maximum areas mapped for the Palaeozoic and the Mesozoic to Cainozoic of about 1.5 x 10^6 km^2 would have distorted the curve further. The percentage of total marine environment was calculated from the area measurements for each time slice and then adjusted to the maximum area. These adjusted values were scaled from 0 to 1. They were then plotted against geologic time at the mid-point of each time slice. An alternative to the adjustment to maximum area mapped would have been the construction of the curve from area measurements within a defined area, for example, the area presently enclosed by the 200m isobath. However, this would have excluded important information for a number of time slices and would also have involved a lengthy procedure using the Intergraph facility, namely the closure of the graphical polygons to the area boundary for 70 time slices.

The degree of resolution of the curve is a function of the number and length of the time slices which, in turn, are dependent on biostratigraphic control. The time slices reflect a generalization of the depositional environments that existed throughout that period of time - variations of environment from the generalized picture are therefore not represented on the curve; this may include regressions and transgressions. Another error inherent in the plot lies in the size of the continental area. For example, high relative values for the early Palaeozoic are largely due to the smaller continental area and the larger areas of oceanic environments in eastern Australia during that time. Also, there are extensive areas of 'unknown' environment on some Palaeozoic maps which could, in part, represent areas of marine deposition. The use of non-palinspastic palaeogeographic maps as the data base also affects the accuracy of the inundation curve. Notwithstanding these limitations, the relative position of the data points to each other will give a close approximation of the degree of inundation of Australia during the Phanerozoic.

Inundation curves and palaeoenvironment plots for individual basins were constructed from area measurements using a digital planimeter. The percentage values of marine flooding did not need adjustment to a common area because the basin boundaries chosen lie within the areas mapped for the time slices. The degree of inundation is therefore shown in percent of marine flooding. The locations of basins selected for this study are given in Figure 1. The global geologic events plotted in Figures 3 to 9, 11 and 13 are based on the compilation of Harland & others (1982).

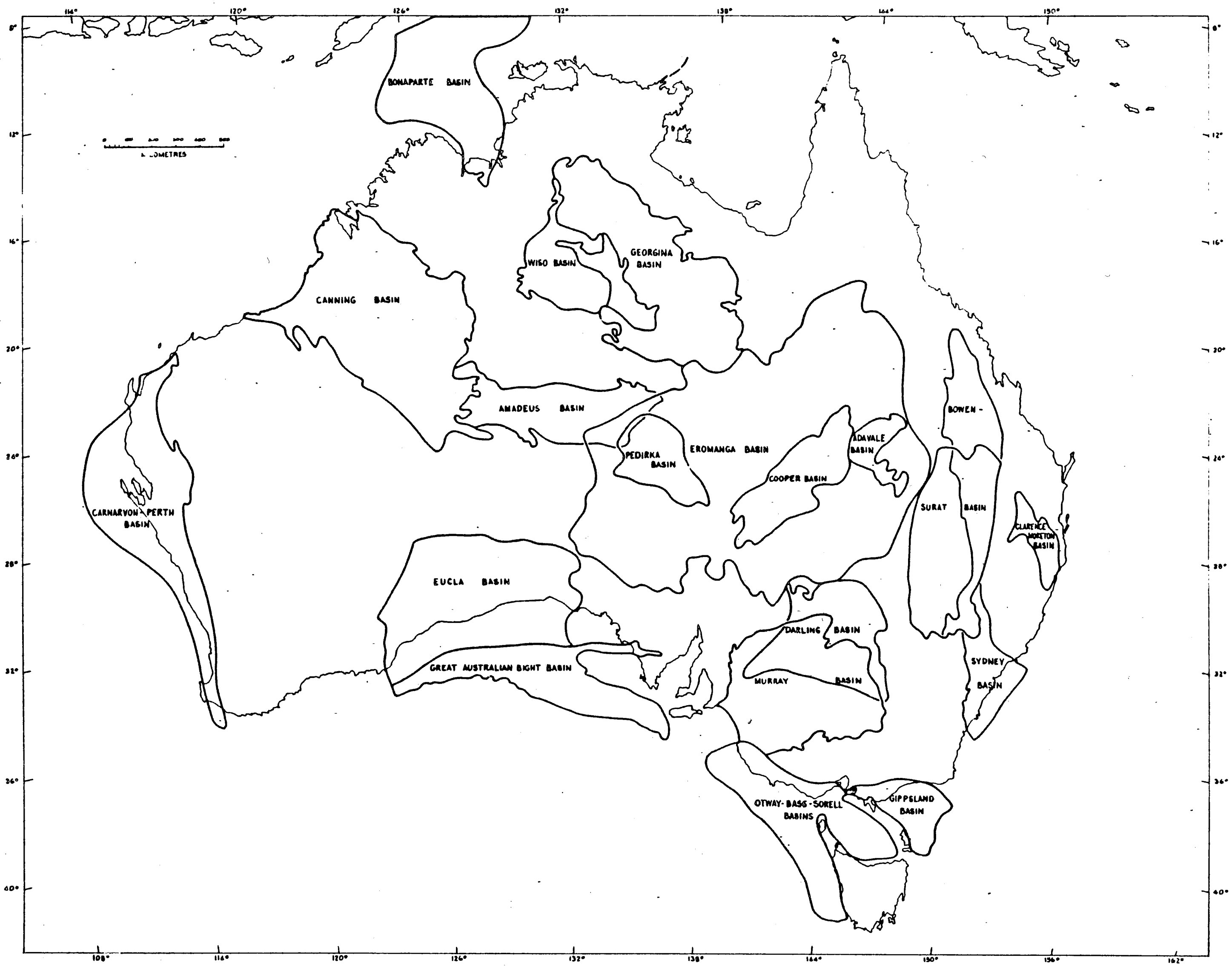


Figure 1: Location of sedimentary basins used for the construction of marine flooding curves.

3.3 RESULTS

The Phanerozoic inundation curve for Australia is shown in Figure 2. The most extensive flooding of the continent occurred in the early Middle Cambrian and in the Early Cretaceous. High values for the Cambrian are probably in part an artefact because of the above mentioned smaller continental area. After a Late Cambrian regression and a transgression in Ordovician Time Slice 2 (TSO 2), relative sealevel gradually fell during the Ordovician and most of the Silurian. Although flooding of western Australian basins occurred in the Early Silurian (TSS 1), the Silurian was a period of relative lowstand of sealevel. The Devonian is characterized by a number of regressions and transgressions with a highstand occurring in Time Slices 7 to 9 (Frasnian/Famennian). A major regression occurred at the Devonian/ Carboniferous boundary and relative sealevel remained low for most of the Carboniferous. The Early Permian experienced a major transgression corresponding to the waning of the Late Carboniferous to earliest Permian glaciation in Gondwanaland. The Permian (TSP 2) to the end of the mid-Jurassic (Callovian, TSJ 7) is marked by a major regressive phase. After a late Jurassic transgression and earliest Cretaceous regression, an extensive inundation of the continent followed, reaching its peak in TSK 4 (Aptian). The sea retreated during TSK 5 to 9 after which the rate of regression decreased. The Tertiary is characterized by three major transgressions in the Eocene, Miocene and Pliocene, and four major regressions in the Paleocene to Eocene, Oligocene, late Miocene and the Quaternary.

Few examples of sealevel curves covering the entire Phanerozoic have been published, although a large number of curves for the various geologic periods exist. As examples of Phanerozoic sealevel changes, curves given by Hallam (1984) and Vail & others (1977b) have been plotted against the Australian inundation curve in Figure 2. Hallam's curve is a plot of continental inundation based on a set of global palaeogeographic maps using a similar method to that used in this report. The original curve of Vail & others (1977b) is now termed a coastal onlap curve by the Vail team and more refined curves for the Mesozoic to Cainozoic have since been published (Haq & others , 1987). These will be compared with Australian curves later in this report. The broad trend, however, of the first and second order cycles showing major

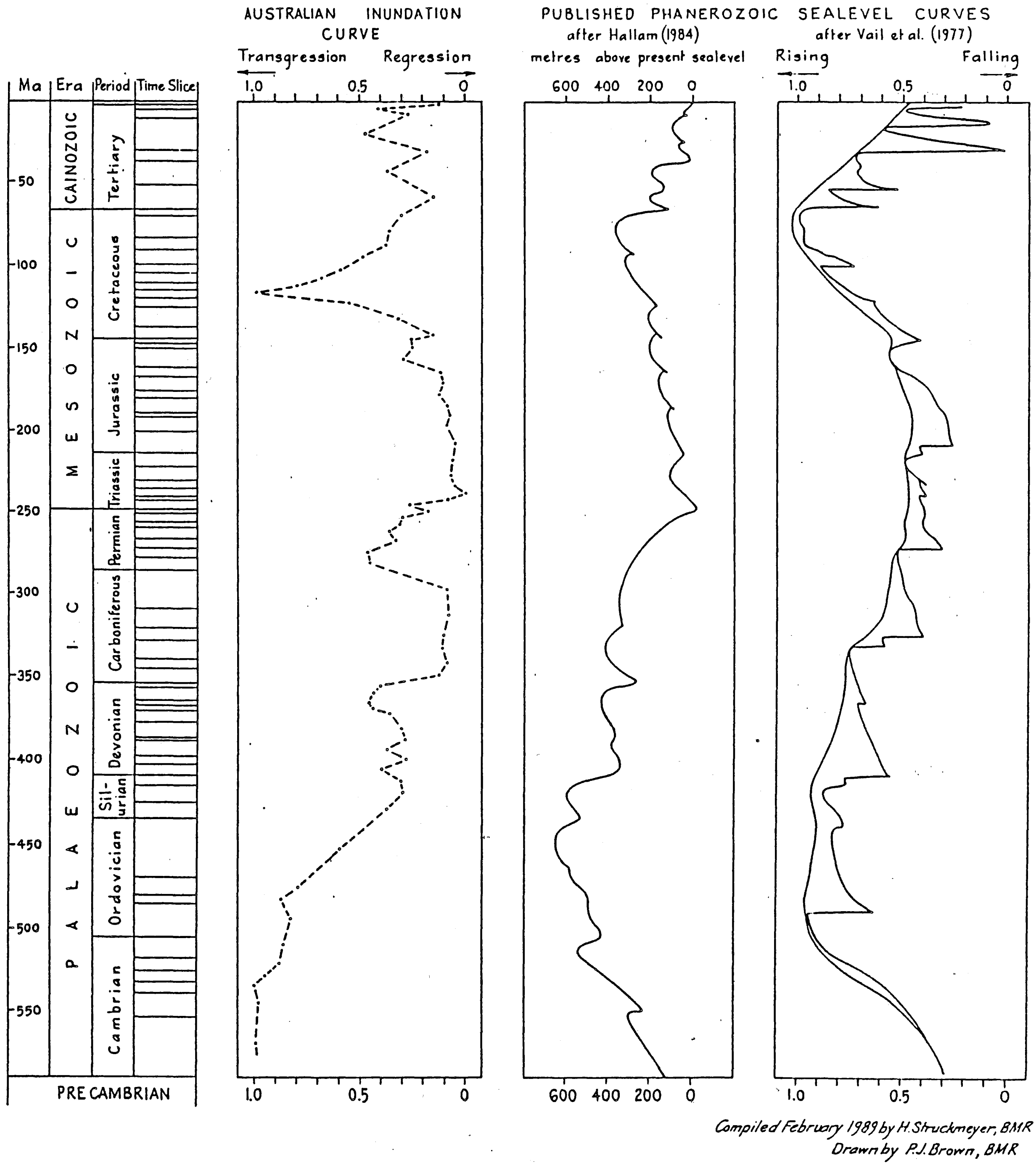


Figure 2: Phanerozoic inundation curve of Australia and global sealevel curves of Hallam (1984) and Vail & others (1977b).

highstands and lowstands is still valid, although biased towards the Atlantic margins of Europe and America.

Points of agreement between the three curves shown in Figure 2 are the Late Devonian transgression, the Triassic to Jurassic lowstand and the transgressive-regressive phases of the Tertiary. A Late Cambrian highstand of relative sealevel is not apparent on the Australian curve; this period is marked, instead, by a regression. The Silurian transgression is also not present. The Late Cretaceous highstand postulated by the two published curves and which is supported by evidence from most regions of the world is not recognizable in Australia, where the main Cretaceous flooding event occurred in the Aptian. The Australian curve does, however, show a decrease in the rate of regression.

Some of the Triassic to Jurassic regressions and transgressions shown in the Australia-wide curve show good correlation with those of Hallam's curve, and to a lesser degree with Vail's curve. This may indicate that these events were indeed of a global nature. Disagreements between the curves could partly be ascribed to difficulties in correlating the time scales used or to the lack of biostratigraphic control for certain geologic periods. Disagreements as well as agreements between the curves could, however, also indicate times when movements of the coastline were not due to eustasy changes but to epeirogenic/tectonic movements. These in turn could also overprint, reverse or enhance a eustatic event.

In an attempt to contribute to the discussion of some of these problems the following sections give a review of relative sealevel changes for each geological period and possible causes for these changes.

Cambrian

Relative sealevel curves showing the percentage of marine flooding for four Australian basins during the Cambrian are given in Figure 3. The Australian inundation curve and those of Vail & others (1977b) and Hallam (1984) are plotted for comparison. One of the major problems in early Palaeozoic correlation between the curves is the lack of diagnostic dating in many areas. This would apply equally to the published curves. Of the basins shown (Figure 3), the Georgina and Amadeus Basins are comparatively well dated. In these

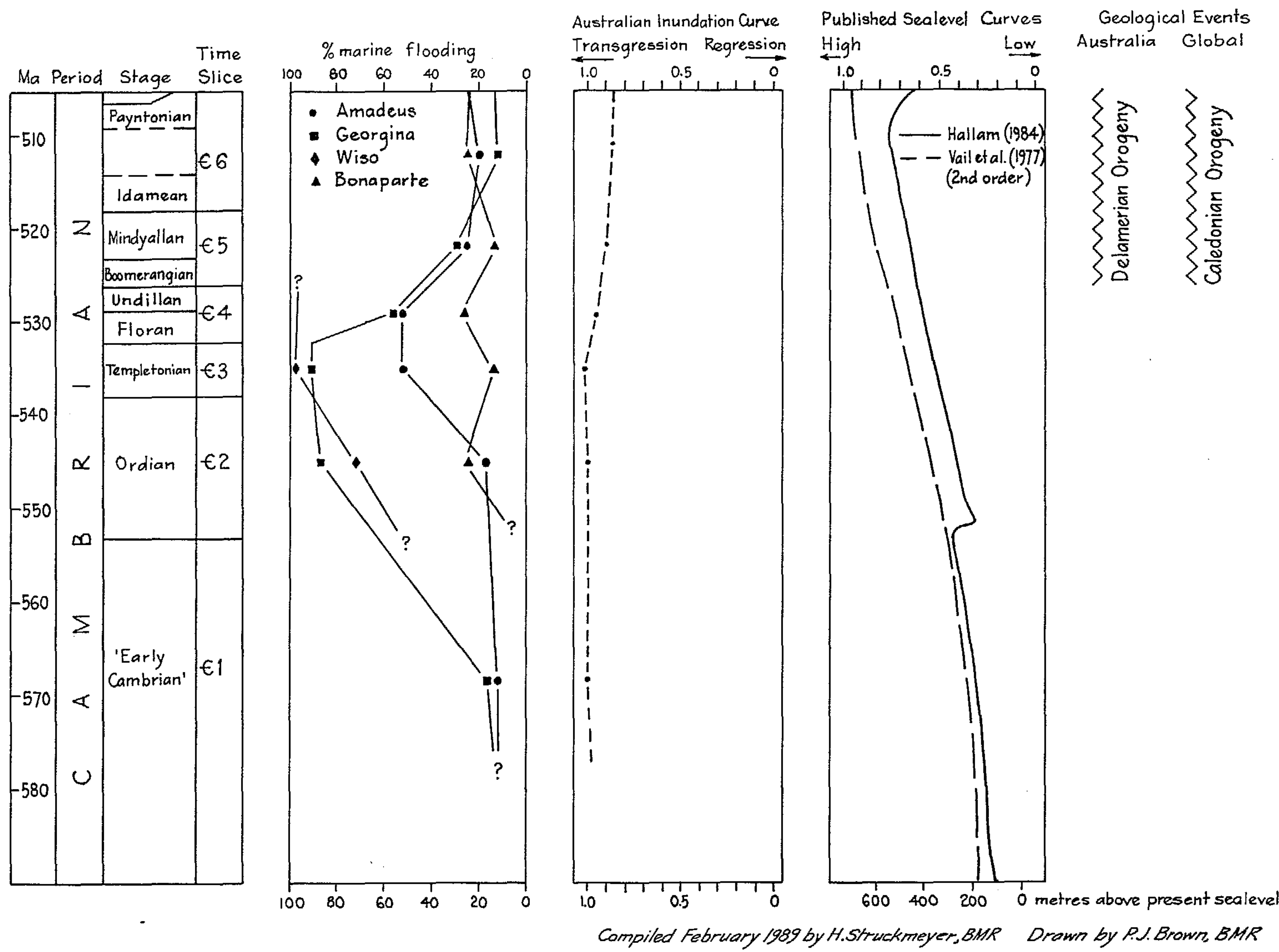


Figure 3: Correlation of relative sealevel curves and geological events for the Cambrian.

basins, as well as in the Wiso Basin, the greatest amount of marine flooding occurred in Time Slices 2 to 3 (late Ordian/early Templetonian). This reflects the development of a transcratonic seaway (see also Cook, 1988) during the early middle Cambrian. Time slices 5 to 6 are characterized by a major regression, which can not be correlated with the two published curves. A major geological event occurring during this time was the Delamerian orogeny, which may have caused the regression in Australia. However, the beginning of the Caledonian orogeny in the 'northern hemisphere' is apparently not reflected on the published sealevel curves. The curve for the Bonaparte Basin shows a deviation from those of the other basins. This may be ascribed to the varying amounts of 'unknown environments' in this area (white areas on maps) during the Cambrian.

Ordovician

With the exception of a transgression in Time Slice 2, the Ordovician period in Australia was a time of gradual regression from the highstand in the mid-Cambrian. The TSO 2 transgression reflects the development of the Larapintine Seaway which gradually retreated during the remainder of the Ordovician (see also Nicoll & others, 1988). Figure 4 shows marine flooding curves for five Australian basins. In the Bonaparte, Georgina and Wiso Basins, where the flooding curves generally agree with the Australian curve, the shallow sea began to retreat before Time Slice 3. The Amadeus and Canning Basins experienced a relative rise in sealevel during TSO 3 indicating that the Larapintine Seaway remained open until at least the Darriwilian. More recent work (e.g. Nicoll & others, 1988) indicates that this also applies to the Georgina and Wiso Basins. Therefore, the differences between the basins may, in part, be due to a lack of diagnostic dating and the uncertainty of biostratigraphic correlation. There is, however, general agreement between the curves that the end of TSO 3 is marked by a major regression indicating the retreat of the shallow sea from the Australian craton.

Comparison with published sealevel curves (e.g. Vail & others, 1977b; Hallam, 1984; Fortey, 1984; see Figures 2 and 4) indicates that there is little agreement between the curves for the Early Ordovician (TSO 1 to 3) and major disagreement for the Late Ordovician (TSO 4). Fortey (1984) described a major regression for the Datsonian/Warendian (early Tremadoc) and Miller (1984)

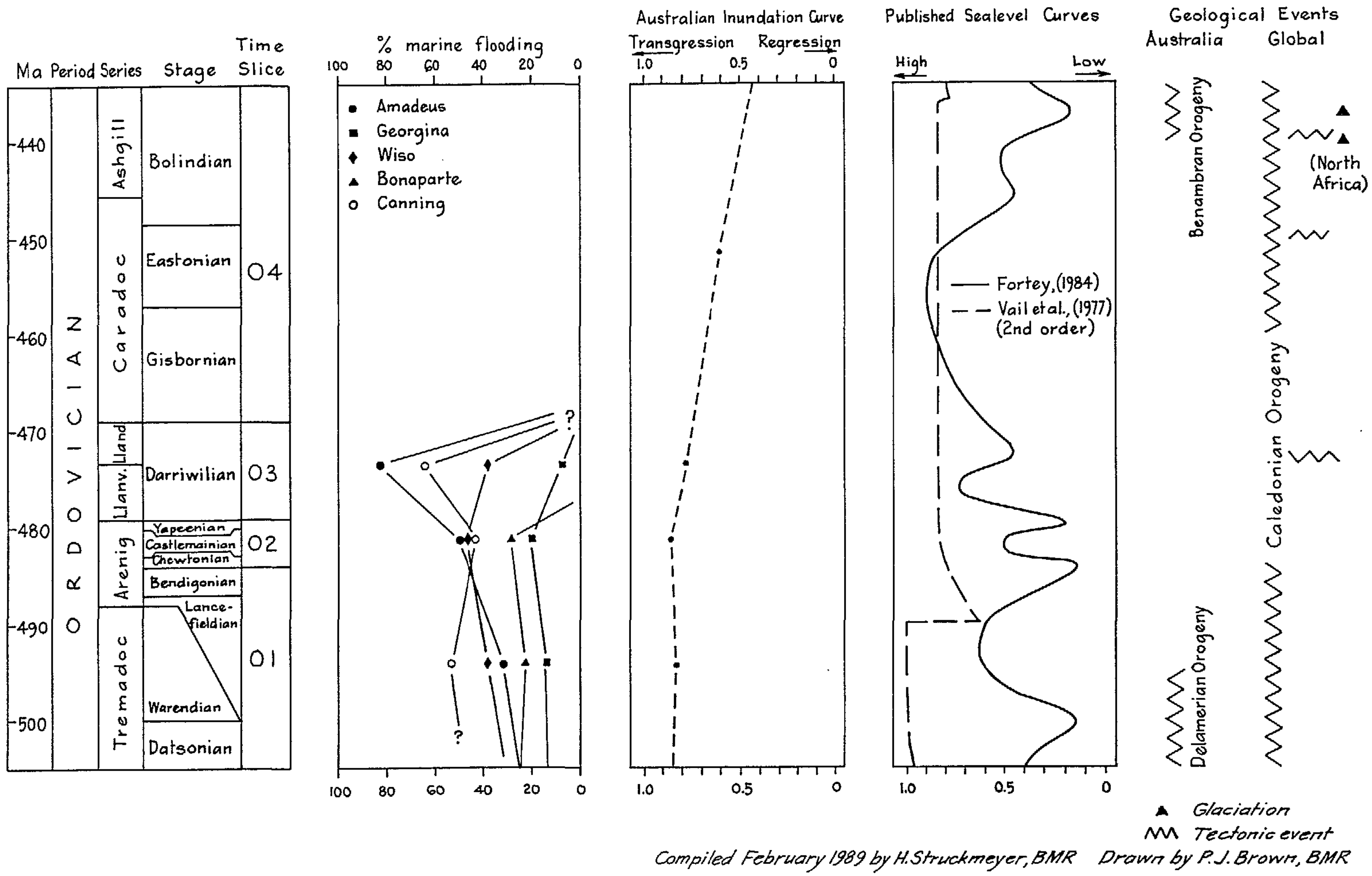


Figure 4: Correlation of relative sealevel curves and geological events for the Ordovician.

recognized two world-wide low sealevel events in the early and the middle Tremadoc. These may possibly be correlated with the relative lowstand in TSO 1 but generally, time slice resolution for the Australian inundation curve is too low for such detailed correlation. A Warendian (TSO 1) transgression culminating in the Castlemainian (mid-Arenig, TSO 2) is discernible on the Australian curve and may be correlated with either the late Tremadoc or the mid-Arenig transgression described by Fortey (1984). Nicoll & others (1988), Barnes (1984) and Chen (1988a, b) also described high relative sealevels during this time and the highstand appears to reflect a eustatic event rather than a regional tectonic one. Another major transgression in the early Darriwilian (TSO 3) has been recorded from China (Chen, 1988a, b) and Canada (Barnes, 1984), and has been described for Australian basins by Nicoll & others (1988). This event is not noticeable on the Australia-wide curve but is present on the flooding curves for the Amadeus and Canning Basins.

The published Ordovician sealevel curves (Hallam, 1984; Fortey, 1984; Chen, 1988a, b) all depict another major transgressive phase for the Caradoc, an event which is shown as the highest relative sealevel during the Ordovician and is regarded as a global event (Fortey, 1984). In Australia, the Late Ordovician (TSO 4) is characterized by mostly non-marine deposition or non-deposition, although there is some debate about the age of the generally unfossiliferous sediments. Nicoll & others (1988) suggested that early Caradoc (TSO 4) tectonic uplift east of the Amadeus Basin separated the eastern and western parts of the Larapintine Seaway resulting in restricted marine and hypersaline to non-marine conditions in the western part of the former seaway. Towards the end of the Ordovician this regressive phase was probably enhanced by the onset of the Benambran Orogeny in the east and possibly the late Ordovician to early Silurian glacial episode in northern Africa (Hambrey & Harland, 1981).

Silurian

The Australian inundation curve indicates that the Late Ordovician regressive phase continued into Silurian Time Slice 2 (Figure 5). This was followed by a minor transgression in TSS 3. However, the marine flooding curves for three basins from the western and northwestern Australian margin differ considerably from the Australia-wide curve. Following the middle to Late Ordovician

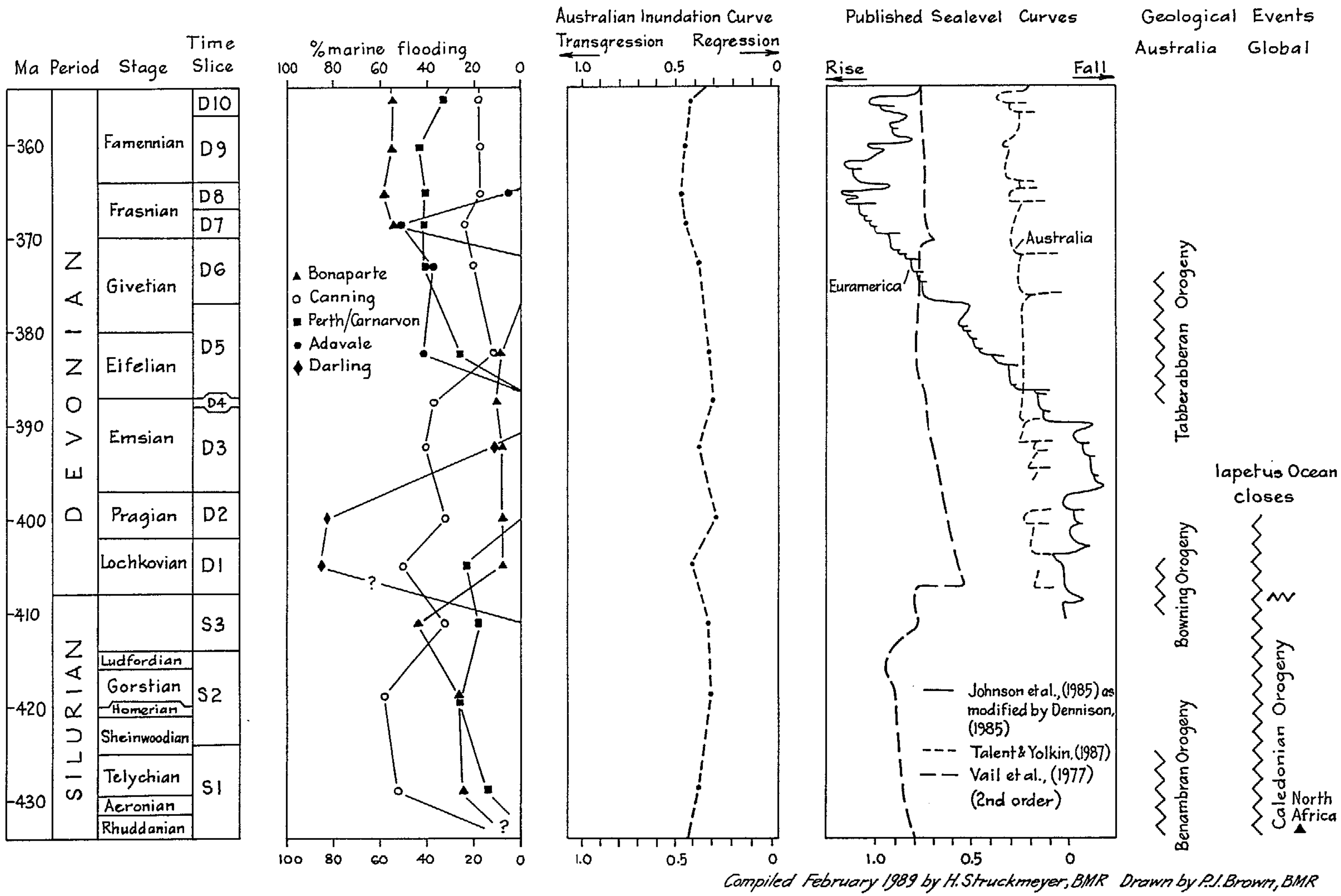


Figure 5: Correlation of relative sealevel curves and geological events for the Silurian and Devonian.

retreat of the sea, these basins experienced marine flooding in the Early Silurian. However, dating of the Silurian sections is loose; the better biostratigraphic control occurs in the Perth/Carnarvon Basin (A.M. Walley, BMR, pers. comm., 1989). In the Canning and the Perth/Carnarvon Basins the widest extent of marine environments occurred in TSS 2, whereas maximum marine incursion in the Bonaparte Basin apparently occurred in TSS 3. A Silurian age for the evaporites in the Bonaparte Basin is, however, tentative and based upon inferred correlation with evaporitic sequences in the Canning and Perth/Carnarvon Basins (Walley & others, in prep.) In the Canning and Perth/Carnarvon Basins, TSS3 is marked by a regression. These variations in relative sealevel may possibly be attributed to local tectonic movements. During the Silurian, non-marine deposition in the Perth/Carnarvon Basin was controlled by movement on the Darling Fault; the TSS 3 regression may therefore be due to a renewed pulse of activity on this fault during this interval. In the Canning Basin, the regression may be related to thermal upwarp initiating the Fitzroy Graben (Brown & others, 1984).

Few publications on Silurian sealevel variations exist (McKerrow, 1979; Johnson & others, 1985). Both Hallam's (1984) and Vail & others' (1977b) curves indicate a latest Ordovician to earliest Silurian lowstand which is followed by a major transgression in the Ludlow (Gorstian to Ludfordian). Johnson & others (1985) argued that the melting of Gondwana glaciers in the Late Ordovician to Early Silurian caused the initial Silurian transgression. The maximum transgression in the Canning and Perth/Carnarvon Basins possibly occurred towards the end of TSS 2, although this is a very tentative conclusion in view of the poor biostratigraphic control. (A.M. Walley, BMR, pers. comm., 1989). The transgression could possibly be correlated with the global highstand postulated by Hallam (1984) and Vail & others (1977b).

Devonian

The Devonian was mapped in 10 time slices giving a comparatively good resolution for the inundation curves. Marine flooding curves for five Australian basins are shown in Figure 5. There is broad agreement between the curves for the western Australian basins (Bonaparte, Canning, Perth/Carnarvon) and the Australia-wide curve: a regression in TSD 1 to 2 was followed by a transgression in TSD 3, a further regression in TSD 3 to 4 and a major transgressive phase from TSD 5 or 6 onwards with a period of maximum marine flooding occurring in TSD 7 to 8.

A different pattern is observed for two eastern Australian basins (Darling and Adavale). In the ?latest Silurian to early Devonian, the Darling Basin was inundated by a shallow sea, possibly advancing from the east and south. The sea retreated again in TSD 2 to 3. This retreat may be connected with the onset of the Tabberabberan Orogeny in southeastern Australia. In the Adavale Basin, the early Devonian was characterized by fluvial to lacustrine depositional environments until a major transgression occurred in TSD 5. This indicates that northeast Australia was beyond the region affected by the Tabberabberan Orogeny.

While recognizing the constraints given by the degree of resolution for the Australian inundation curve as well as problems with time correlation, comparison of the Australia-wide curve and the marine flooding curves for various basins with the published curves suggests that several events may be correlative: the late Lochkovian regression; possibly the mid-Emsian transgression and the late Emsian regression; the Givetian to Frasnian transgression; the Frasnian highstand and the Famennian regressive phase. However, not each of these events is seen in all basins, indicating that either the events are not correlatable Australia-wide or that the differences are due to poor biostratigraphic control. For example, poor dating for the Late Silurian to Early Devonian of the Bonaparte Basin may be responsible for the divergence of its flooding curve from those of the Canning and Perth/Carnarvon Basins.

In a study of Devonian sealevel changes in Eumerica, Johnson & others (1985) identified 14 transgressive-regressive cycles of eustatic origin (Figure 5). According to the authors, major sealevel falls occurred in the late Lochkovian, at the Pragian/Emsian boundary, in the late Emsian, the early Givetian, at the Frasnian/Famennian boundary and at the Devonian/Carboniferous boundary. Talent & Yolkin (1987) compared the curve given by Johnson & others (1985) as modified by Dennison (1985) with sealevel changes interpreted from sediments in Australia and West Siberia. They suggested that the early Emsian and early Frasnian transgressions shown on Johnson's curve are correlatable which would indicate that these are global events. They also contended that, probably due to orogenesis, a mid-Givetian transgression is not recognizable in Australia. However, the flooding curves and the inundation curve in Figure 5 show that this event is recognizable in areas not effected by the Tabberabberan Orogeny.

Johnson & others (1985) pointed out that glaciations as well as the desiccation of large basins cannot be invoked as causes for eustasy fluctuations during the Devonian, because the volume of Devonian evaporites is too small to account for major eustatic changes. They suggested that changes in ridge crest volume may have been the major cause for Devonian sea level changes. However, the frequency of the short-term fluctuations described by these authors appears to be too high for the periodicity of ridge volume changes as postulated by Pitman (1978).

Carboniferous

According to the Australia-wide inundation curve, a major regression at the Devonian/Carboniferous boundary resulted in a general lowstand of relative sealevel in the Carboniferous (Figure 6). A minor transgression occurred in TSC 3, followed by a gradual fall of relative sealevel in TSC 4 to 5. This appears to correspond with a major fall in sealevel in the mid-Namurian shown on published sealevel curves by Ross and Ross (1987) and Vail & others (1977b). Ross and Ross (1987) used sequence stratigraphic methods to construct a eustatic curve from North American depositional sequences. They identified more than fifty third order sequences in the Carboniferous most of which occur in the Late Carboniferous. They suggested that these cycles are the result of glaciation with other causes being superimposed on the smaller cycles. The resolution of the Australia-wide curve does not permit comparison to the level of the 3rd order cycles, but some changes shown on the 2nd order curve given by Ross and Ross (1987) may possibly be correlated.

Roberts (1985) interpreted Carboniferous sealevel changes from depositional patterns in various areas of Australia. He identified two major regressions during the Carboniferous which correlate across Australia. The first, which occurred at approximately the Tournaisian/Visean boundary, is interpreted as a eustatic fall in sealevel. This fall may correspond to the regression noticeable on the Australia-wide curve in TSC 1 to 2. A second major

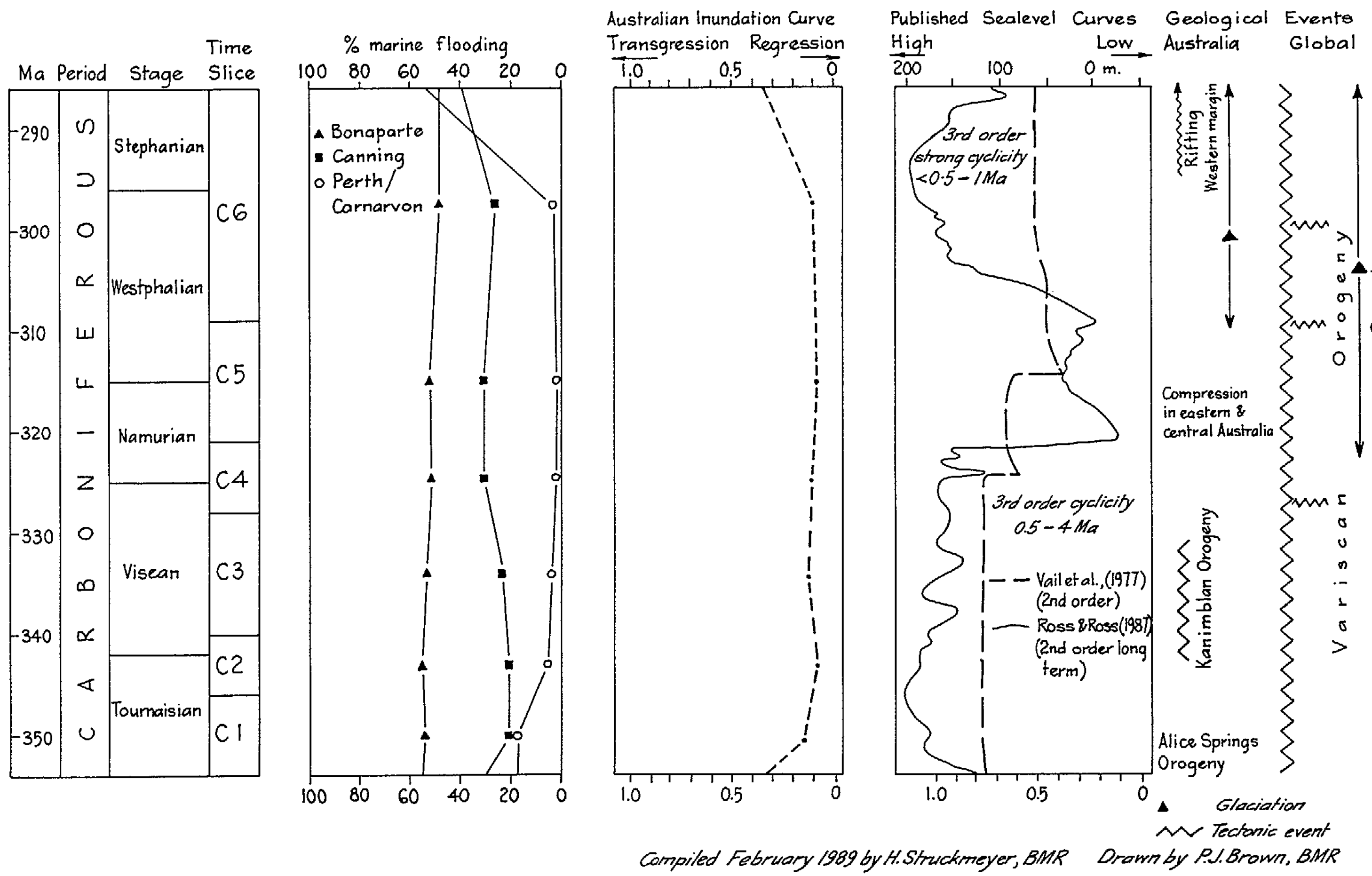


Figure 6: Correlation of relative sealevel curves and geological events for the Carboniferous.

regression in the Westphalian, interpreted by Roberts (1985) as a result of arching along the western margin of the continent, possibly enhanced by glacio-eustatic fluctuations, is also present on the Australia-wide curve (TSC 5).

There is no indication of a global event which could have caused the major regression at the Devonian/Carboniferous boundary. The Gondwana glaciation probably did not commence before the Namurian (Hambrey & Harland, 1981) and in Australia, glacial deposits are generally not older than Westphalian. In North America, the beginning of the Gondwana glaciation is reflected in a major regression in the Namurian and the presence of cyclothemic deposition (Ross & Ross, 1987; Veevers & Powell, 1987). Only a minor regression is observable on the Australian curve for this time and the flooding curves for the basins show no evidence for a major regression. This may be due to the degree of resolution.

Permian

A ?Late Carboniferous to Early Permian rise in relative sealevel is evident on the Australian curve and on flooding curves for the Canning and Perth/Carnarvon Basins (Figure 7). During this time, the first marine sediments were also deposited in the Sydney-Bowen Basin. The transgressive phase continued into the Sakmarian (TSP 2) until a fall in relative sealevel took place in TSP 2 to 3. Marine flooding curves for the Bonaparte and Perth/Carnarvon Basins also show a regression during this time, whereas the transgressive phase persisted in the Sydney-Bowen and the Canning Basins. A gradual regression which commenced in TSP 4 to 5 and culminated in a pronounced lowstand in the latest Permian is visible on the marine flooding curves and the Australia-wide curve, although maximum flooding in the Sydney-Bowen Basin occurred in TSP 5 prior to the major regression in TSP 6 and 7. The eastern margin of Australia was a tectonically active margin during the Permian and it is likely that relative sealevel changes were at least in part tectonically controlled. However, there is general agreement between all basins and the published curve (Ross & Ross, 1987) that a lowstand occurred in the latest Permian indicating that it may have been of eustatic origin.

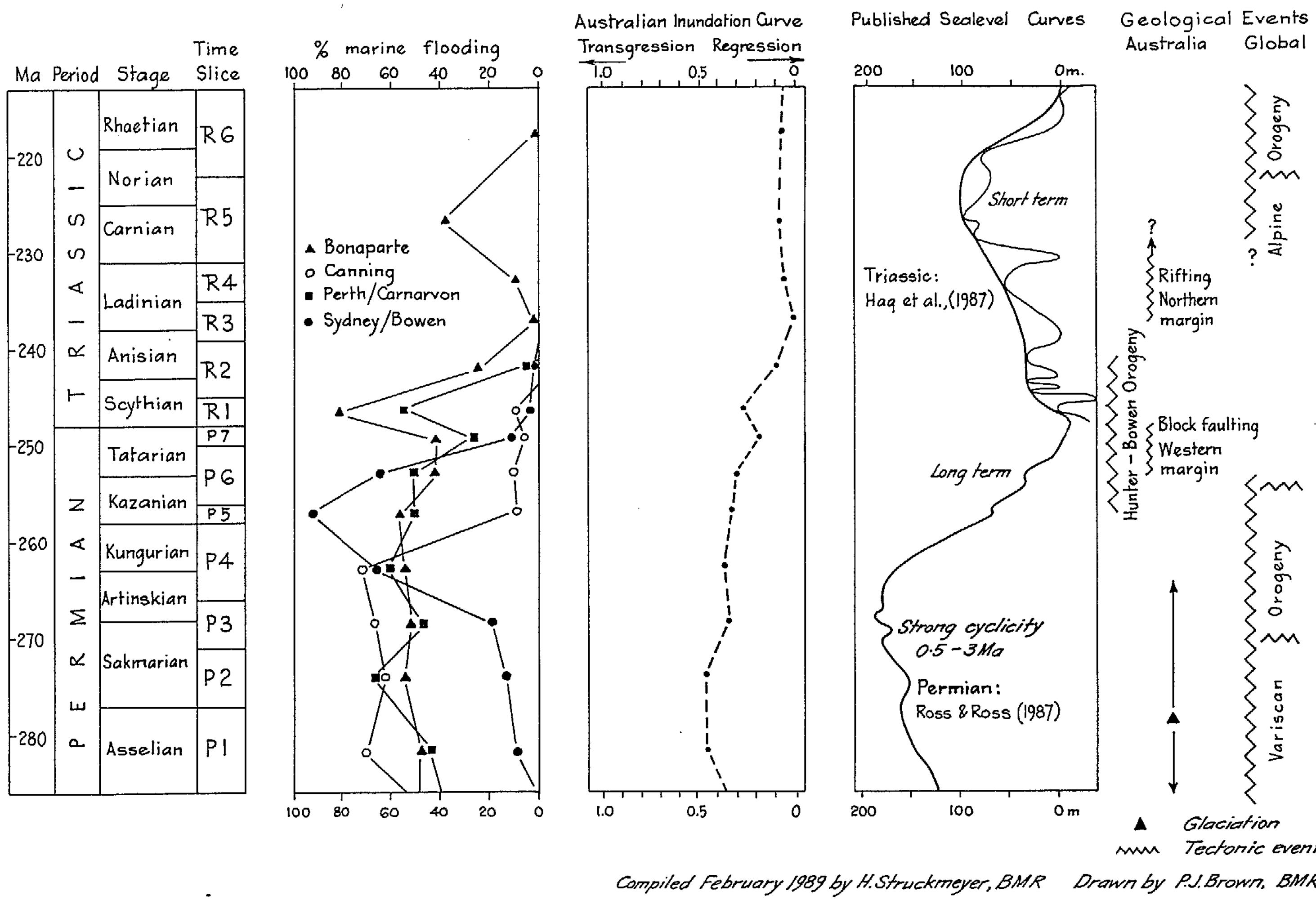


Figure 7: Correlation of relative sealevel curves and geological events for the Permian and Triassic.

The latest Carboniferous to earliest Permian (TSP 1) was a period during which Australia experienced the widest distribution of glacial deposition related to the Late Carboniferous to Early Permian glaciation of Gondwanaland. This period was also characterized by a major marine transgression. The marine component of TSP 1 is probably a function of initial loading of the crust by ice and, later in the time slice, a marine transgression following the retreat of the ice.

Triassic

With the exception of an Early Triassic (TST 1) transgression following the Late Permian regressive phase, the Triassic was generally a period of low sealevel in Australia (Figure 7). The early transgression is visible on the Australia-wide curve and the marine flooding curves for selected basins, although the Sydney-Bowen Basin was marked by further retreat of the sea in the Early Triassic; this can probably be ascribed to continuing but waning tectonic activity related to the Hunter-Bowen Orogeny. A major regression took place in late TST 1 to TST 3 with the Triassic lowstand of relative sealevel occurring in TST 3. This was followed by a minor transgression in TST 4 to 5. The Australia-wide curve indicates that relative sealevel remained stable in the Late Triassic. A mid- to Late Triassic transgression is also noticeable on the marine flooding curve for the Bonaparte Basin, but the advancing sea does not appear to have reached the Canning and Perth/Carnarvon Basins.

Haq & others (1987) published a revised cycle chart of the Triassic based on sequence stratigraphy; they distinguished nine 3rd order cycles on the resulting eustatic curve. A 1st order eustatic rise in the early Triassic (TST 1) correlates with the transgression evident from the Australia-wide curve. The mid-Triassic regression in Australia can possibly be correlated with the Anisian/Ladinian short term fall in eustatic sealevel on the Haq & others curve. The Late Triassic highstand depicted on the eustatic curve and which is also shown on Hallam's curve is not apparent on the Australian curve, but it corresponds to marine flooding in the Bonaparte Basin in TST 5.

Jurassic

Relative sealevel remained low for most of the Jurassic (Figure 8). Deposition occurred mostly in fluvial to lacustrine environments, and marine to coastal environments were restricted to the northwestern and western margins. Marine flooding curves for basins from these areas therefore determine the shape of the Australia-wide curve. Minor transgressions occurred in TSJ 2 and 5, and a major transgression occurred in the Late Jurassic (TSJ 8). Hallam (1984) suggested that Jurassic eustasy was characterized by "interrupted sea-level rise to an Oxfordian-Kimmeridgian maximum", a period marked by deposition of marine claystones and major reef building across northwestern Europe. This trend of intermittent rise of relative sealevel is also recognizable on the Australian inundation curve.

Some agreement exists between the eustatic curve of Haq & others (1987) and the Australian inundation curve, for example, a transgressive phase in the Bajocian and a Late Jurassic rise in sealevel. The highstand on the eustatic curve, however, coincides with a regression on the Australian curve in the early Tithonian, but this disagreement may be related, in part, to difficulties of biostratigraphic correlation for the Late Jurassic. In Australia, the Late Jurassic rise in relative sealevel may be the result of the breakup of the northwestern margin in the Callovian to Oxfordian. Worldwide, the period from the mid-Jurassic onwards was also characterized by increasing seafloor spreading events (Kennett, 1982), with spreading rates in the central Atlantic increasing in the Late Jurassic (Ziegler, 1988). Recent interpretation of ODP drilling results (Leg 123, Sites 765 and 766) from the Argo Abyssal Plain and the deepwater Exmouth Plateau indicate that the oldest seafloor along the northwestern margin of Australia may be as young as Early Cretaceous (Gradstein & others, 1989). This probably needs further investigation, but if confirmed, would require changes to palaeogeographic maps for the time slices concerned; this would therefore reduce the degree of marine inundation on the Australia-wide curve and the marine flooding curves for the Late Jurassic.

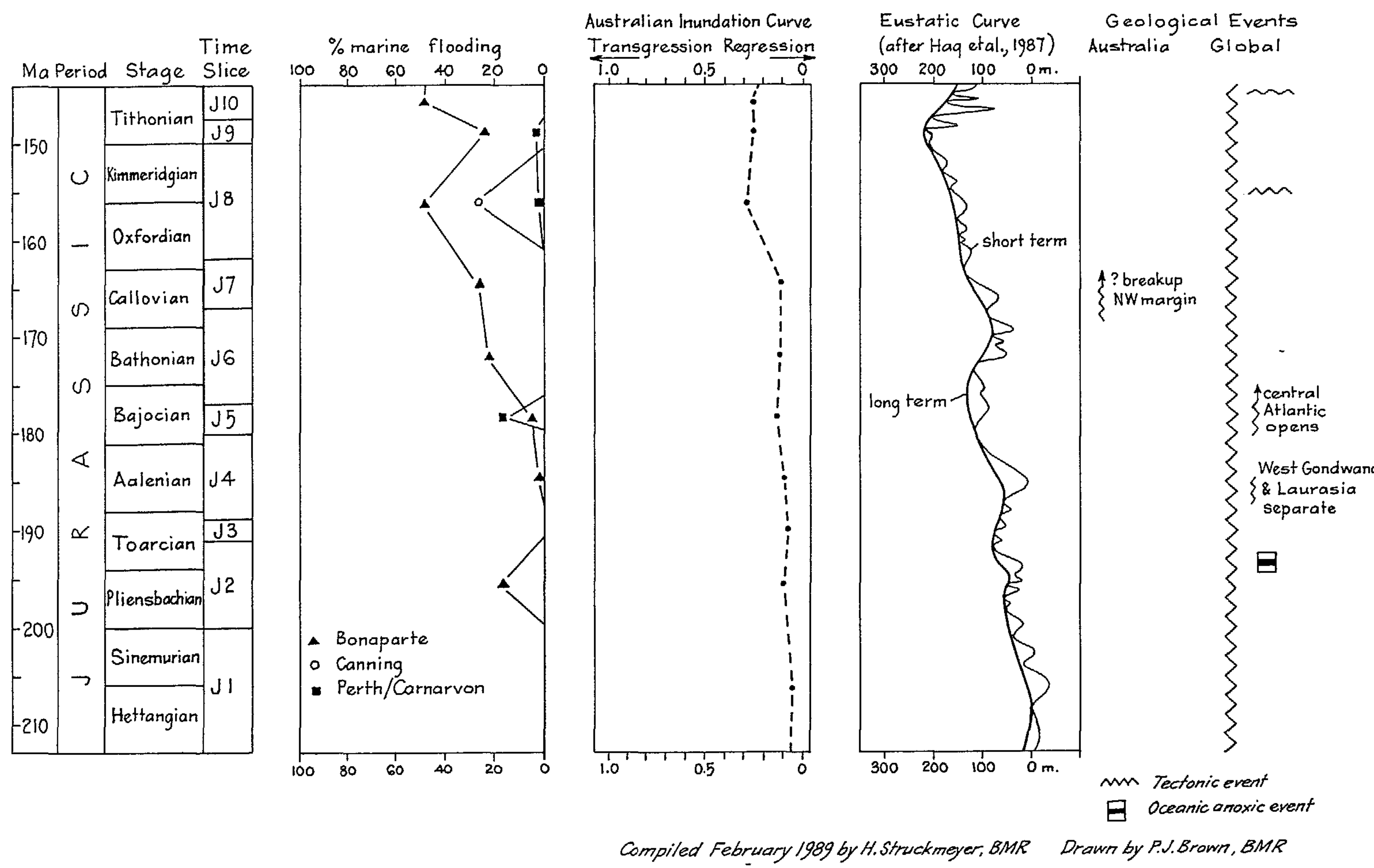


Figure 8: Correlation of relative sealevel curves and geological events for the Jurassic.

Cretaceous

The Australian inundation curve for the Cretaceous (Figure 9) shows that, following a regression in TSK 1, a major inundation of the continent occurred in the Early Cretaceous culminating in the Aptian (TSK 4). This highstand was followed by a gradual regression in the Albian to Maastrichtian. The Australian curve differs considerably from the generally accepted view of a global sealevel highstand in the Late Cretaceous.

A great number of papers have been published on Cretaceous sealevel changes from various regions of the world and only a few of these can be considered in this report. Cooper (1977) suggested the presence of thirteen to fourteen eustatically controlled transgressions with a maximum occurring in the Maastrichtian. Schlanger and Jenkyns (1976) constructed a relative sealevel curve on the basis of the occurrence of 'Oceanic Anoxic Events' showing that the widest distribution of black shales occurred in the late Cenomanian to Turonian. Vail & others (1977b) postulated a general rise in sealevel for the Cretaceous interrupted by a minor regression in the Aptian and a major regression in the Cenomanian with a highstand occurring in the Campanian to Maastrichtian. According to Hancock and Kauffman (1979), the Cretaceous highstand in North America took place in the Cenomanian/Turonian, whereas in northern Europe, it occurred in the Maastrichtian (Figure 9). Haq & others (1987) revised the Vail cycle chart and contended that the maximum sealevel stand occurred in the Cenomanian to Turonian with a further, but less extensive highstand in the Campanian (Figure 9). The mid-Aptian sealevel fall postulated by a number of authors was also recognized in Australia (Morgan, 1980; Burger, 1986).

Marine flooding curves for various basins are given in Figure 10. They are grouped into three columns - western margin, southern margin and Mesozoic intracratonic basins. The Bonaparte and Perth/Carnarvon Basins differ considerably from the Australian curve, because they show a continuous transgression in the Early Cretaceous peaking in TSK 4. This is followed by a regression in TSK 5, a transgression in TSK 6, a regression in TSK 7 and a transgression in TSK 8. From TSK 8/9 onwards the two curves digress with the Bonaparte Basin showing a gradual regression culminating in the Maastrichtian. In the Perth/Carnarvon Basin, relative sealevel continued to rise into TSK 9, remained stable in TSK 9 to 10 and fell from TSK 10 to 11. The Cenomanian highstand in the Bonaparte Basin may possibly be correlated with the eustatic high postulated by Haq & others (1987) and the highstand in TSK 9 to 10 in the Carnarvon Perth may correlate with the Campanian rise in sealevel. Although differences exist, the shape of the curves for basins from the western margin correlates relatively well with the eustatic curve.

Marine flooding curves for three basins or basin groups from the southern margin (Great Australian Bight Basin, Otway/Bass/Sorell Basins, and Gippsland Basin) show a reverse trend to that of the Australia-wide curve. A continuous transgression from the Aptian onwards occurred in the Bight Basin. The Otway/Bass/Sorell and Gippsland Basins were flooded in Time Slice 8 (Cenomanian). These basins also experienced a continuous transgression until TSK 10, after which a regression occurred in the Gippsland Basin. The southern basins were inundated in response to the breakup of the southern margin and their flooding reflects the advancing southern ocean. The curves show continuously rising relative sealevel reflecting a cause and effect relationship between subsidence and rise of relative sealevel. Therefore, the use of young margins for estimations of eustatic sealevel changes may not be advisable. The transgression in the Bight Basin commenced considerably earlier than in the basins further east. This may record a progressive west to east breakup along the southern margin as suggested by Mutter & others (1985) rather than a synchronous breakup at approximately 95 Ma (Veevers, 1986).

The marine flooding curves for a number of Mesozoic intracratonic basins have a significantly different shape from those from the continental margins (Figure 10). All these basins experienced marine flooding in the Early Cretaceous (TSK 2 to 3) culminating in the Aptian (TSK 4). This was followed by a regression in the Albian. In a detailed study of sealevel changes during the Early and Middle Cretaceous in Australian basins, Morgan (1980) distinguished four regressions (mid-Aptian, early Albian, mid-Albian and latest Albian) within the Early Cretaceous highstand (Figure 9), based on bio- and lithostratigraphic data. These regressions and associated transgressions cannot be recognized on the flooding curves but this is probably due to resolution as the time slices represent a generalized picture of the palaeoenvironment during that period of time. There is agreement, however,

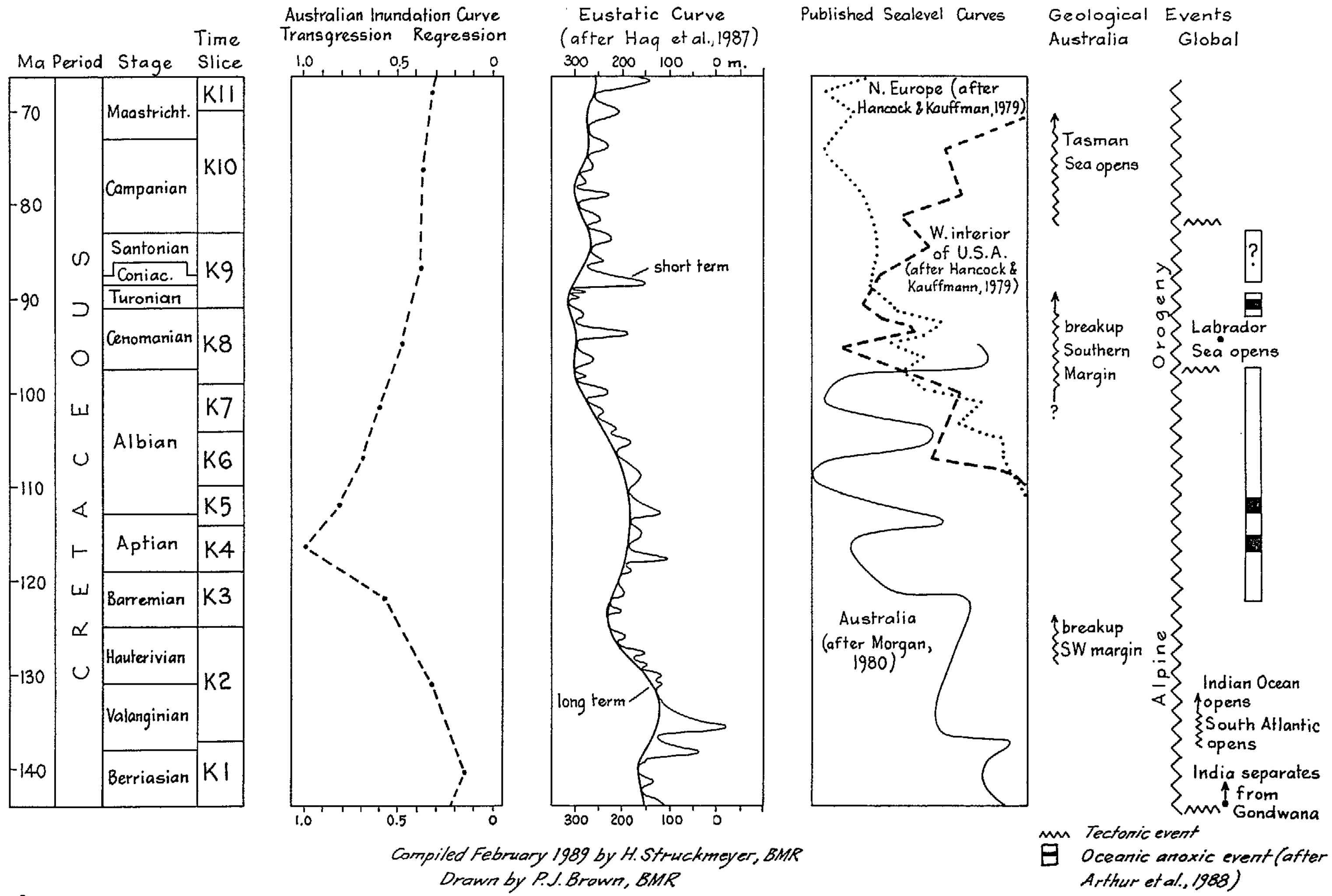


Figure 9: Correlation of relative sealevel curves, eustatic sealevel curve and geological events for the Cretaceous.

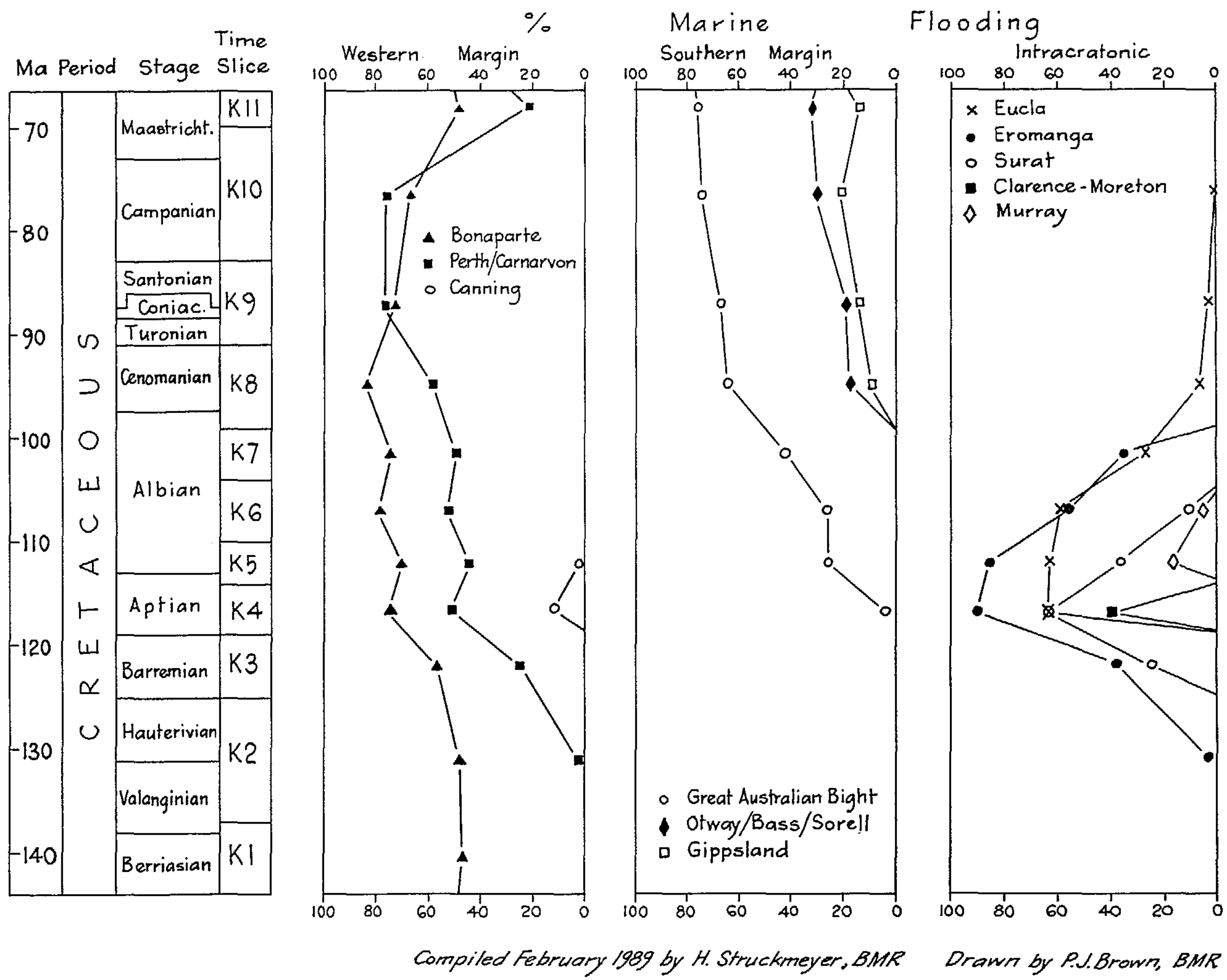


Figure 10: Marine flooding curves for Australian Cretaceous basins.

between Morgan's data and those given here that, in the intracratonic basins, the sea had retreated by the end of the Albian. A minor divergence from this trend is observable for the Eucla Basin, where minor and decreasing areas of marine environments were present until TSK 10.

Morgan (1980) argued that eustatic changes of sealevel are best studied in simple intracratonic basins. However, the present study has shown that marine flooding curves for these basins differ considerably from those of the continental margins and this cannot be explained by local tectonic processes operating in the margin basins. Haq & others (1987) based their eustatic curve mostly on data from passive margins, and it is interesting to note that the best correlation between their curve and the marine flooding curves exists for the Bonaparte Basin, where seafloor spreading may have commenced in the Late Jurassic; it was therefore part of an 'established' passive margin during the Cretaceous.

The common point between the flooding curves for basins from the western margin and intracratonic basins is the Aptian transgression; it may reflect a eustatic rise in sealevel corresponding to the Aptian 'short term' rise on the Haq & others' (1987) curve. The wide extent of flooding of the Australian continent in the Aptian may indicate, however, that the postulated eustatic rise was enhanced by a tectonic event. The retreat of the epicontinental sea cannot easily be attributed to a eustatic fall in sealevel. The regression took place throughout the Albian which, according to the eustatic curve, was a period of eustatic rise; it is therefore unlikely that the regression is related to the major eustatic fall in the Cenomanian. Uplift of the Euroka Arch may have initiated the regression by closing the northern seaway (Senior & others, 1978); closure of the connection to the Surat Basin through uplift of the Nebine and Eulo Ridges occurred as early as the Early Albian (Day & others, 1983). An increase in volcanic detritus in sediments of Albian to Cenomanian age (Exon & Senior, 1976) also indicates increasing tectonic activity in eastern Australia.

Summarizing the observations made from the Cretaceous marine flooding curves, it is obvious that a separation of eustatic and tectonic events on relative sealevel curves is difficult. The Australia-wide curve is dominated by the Aptian inundation of approximately half the Australian continent and the following retreat of the sea from this area. Although initial flooding may have occurred as a result of a eustatic rise in sealevel possibly enhanced by epeirogenic movement, the curve is probably not a close approximation of eustatic changes of sealevel during the Cretaceous. Comparison of marine flooding curves for various basins has shown that the shape of these curves depends very strongly on the tectonic setting of the basin during a particular time. The curve for the Bonaparte Basin which, in the Cretaceous, was relatively stable tectonically, shows a comparatively good correlation with the curve of Haq & others (1987), whereas curves for basins from tectonically active margins and intracratonic basins show little correspondence with the eustatic curve.

Cainozoic

The Australian inundation curve shows that, during the Cainozoic, the most extensive inundation of the continent occurred in the Miocene (Figure 11). The Paleocene to Early Eocene (TSCz 1) was marked by a regression and further regressions occurred in the Late Eocene to Early Oligocene, the Late Miocene and the Pleistocene. Periods characterized by transgressions were the mid-Eocene, the Late Oligocene to Early Miocene and the Pliocene. A more detailed record of relative sealevel during the Cainozoic is not possible because of the degree of time slice resolution.

Figure 12 shows marine flooding curves for several Australian continental margin basins. It is apparent that there is general agreement between the curves for most basins (Bonaparte, Perth/Carnarvon, Great Australian Bight and Eucla Basins). The greatest changes in marine flooding occur in the Eucla Basin. The curve for the Great Australian Bight Basin shows only minor changes in marine flooding but these changes correspond to the regressions and transgressions visible on the Australia-wide curve. The marine flooding curves for the basins of southeastern Australia (Otway/Bass/Sorell, Murray and Gippsland Basins) differ from the other flooding curves; they do not show the early Oligocene regression but rather a continuous transgression until TSCz 4. For the Neogene the curves for these basins largely correspond to the Australian curve.

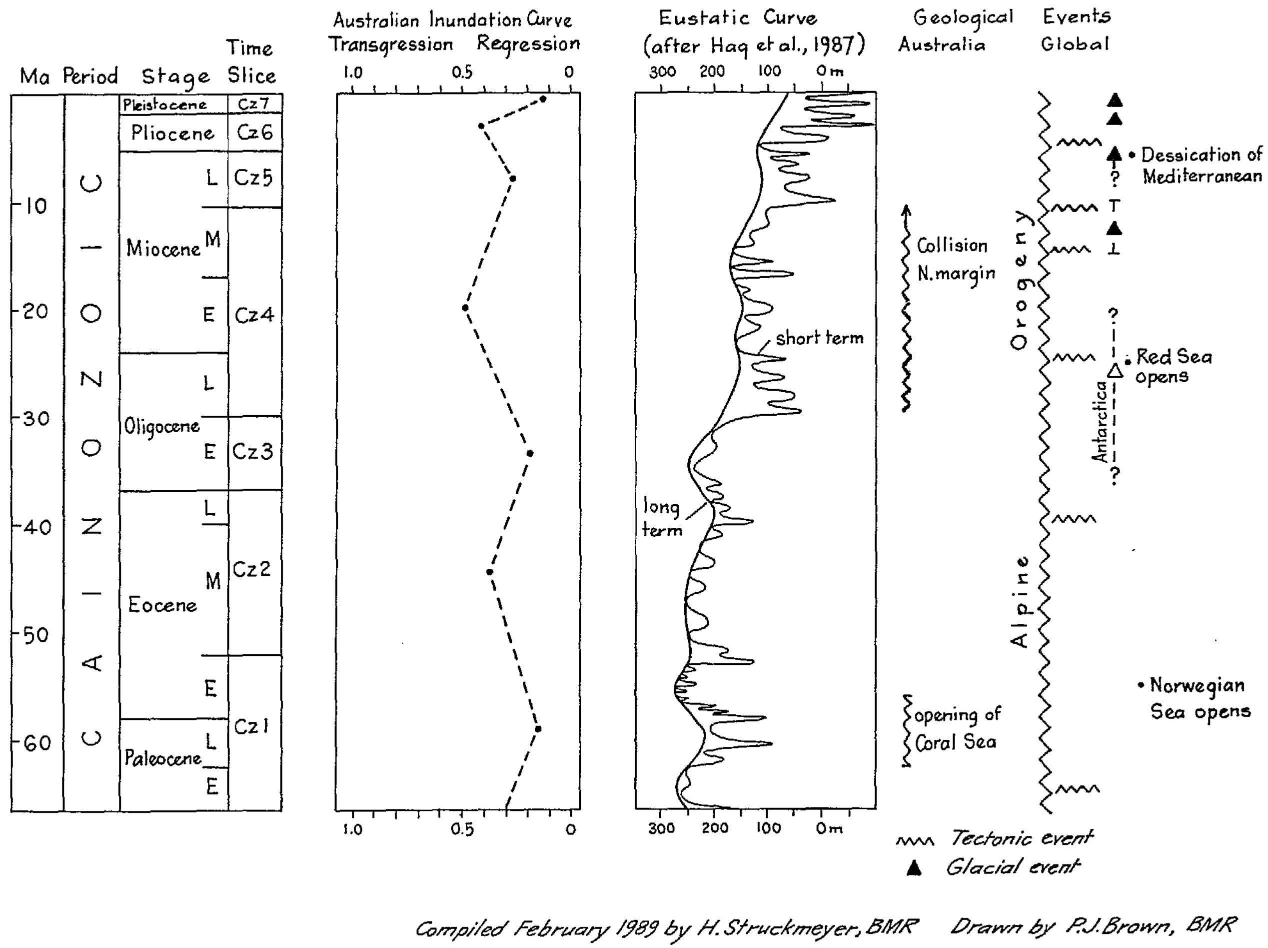
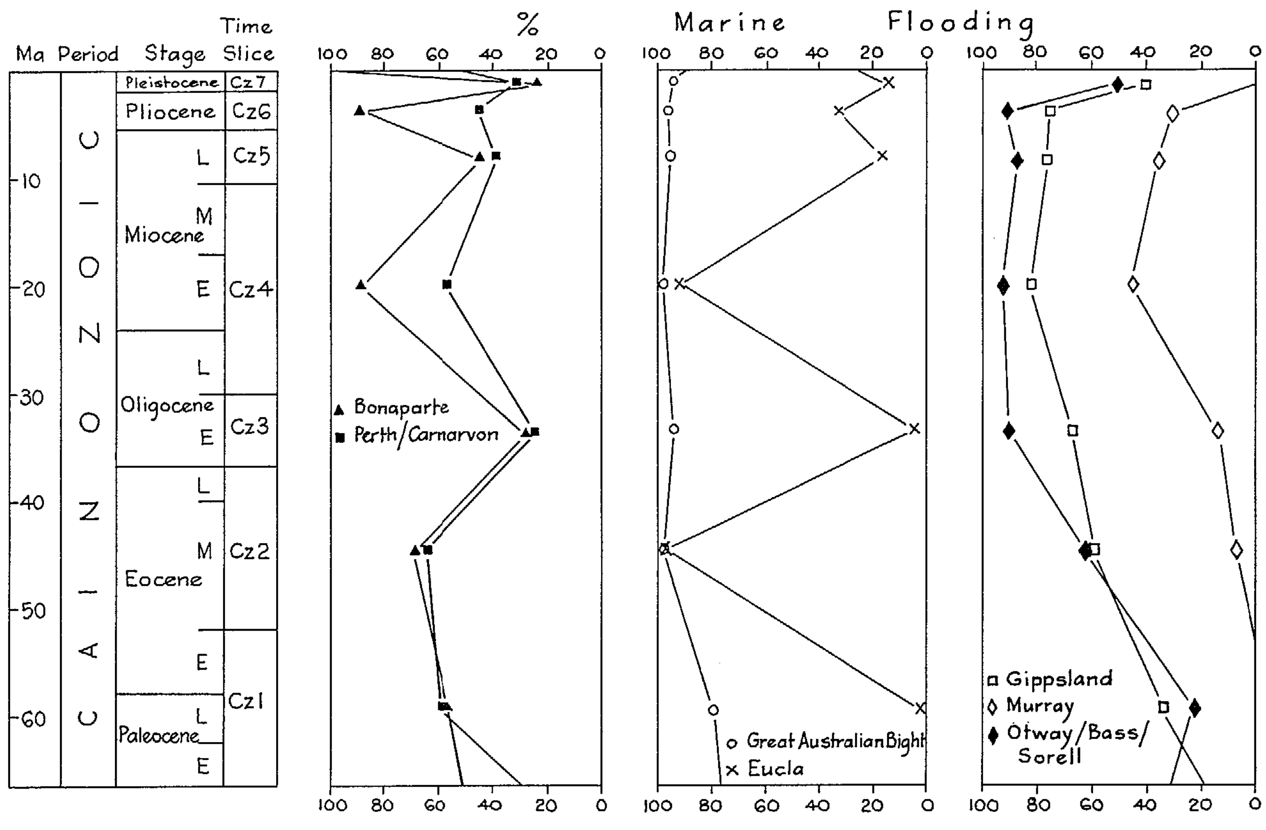


Figure 11: Correlation of relative and eustatic sealevel curves, and geological events for the Cenozoic.



Compiled February 1989 by H. Struckmeyer, BMR   Drawn by P.J. Brown, BMR

Figure 12: Marine flooding curves for Australian Cenozoic basins.

Comparison with the eustatic curve of Haq & others (1987) suggests that the Paleocene lowstand and the Neogene changes in sealevel correspond relatively well with the transgressions and regressions shown on the Australian curve. The major drop in sealevel of close to 200m postulated for the mid-Oligocene is not clearly visible on the Australian curve. It is reasonable to expect that a fall of this magnitude should be reflected on the Australian curve. Compilation of stratigraphic columns for the BMR-AMIRA Palaeogeographic Maps Project has shown that, in most areas of Australia, a major hiatus is present between Late Eocene to early Late Oligocene times. This was followed by transgressive sedimentation in the Late Oligocene (Wilford & others, in prep.). Therefore, the lowstand observable for TSCz 3 reflects a period of non-sedimentation and erosion, but the timing of the onset of this event and the extent of erosion is not known. It is therefore possible that the hiatus reflects a mid-Oligocene erosional event which is correlatable with the fall in sealevel shown on the Haq & others' (1987) curve. However, the absence of the TSCz 3 lowstand from the curves for the southeastern basins contradicts this interpretation. The stratigraphy of the southeastern basins (e.g. Brown, 1986; Thompson, 1986; Wilford & others, in prep.) shows the possible presence of an unconformity at approximately 30 Ma, but this event does not appear to be significant enough to account for a 200m drop in sealevel. There is also no evidence for increasing rates of subsidence in southeastern Australian basins for this time period, which could reduce the effects of a fall in sealevel.

A number of authors have questioned the rapid mid-Oligocene sealevel fall postulated by Haq & others (1987); they proposed instead a major drop in relative sealevel in the early Oligocene (e.g. Olsson & others, 1980; Hallam, 1984; Siesser, 1984). Pitman (1978) suggested a major regression for the Late Eocene to Early Oligocene caused by a decrease in the rate of eustatic sealevel fall in the Late Eocene. According to Shackleton & Kennett (1975) and Wolfe (1978), the Late Eocene to Early Oligocene period was marked by a major cooling event which may have been due to the onset of glaciation in Antarctica. This is supported by a recent study by Feary & others (in prep.) on oceanic oxygen isotope ratios obtained from samples from the northeastern margin of Australia. The data show that the Paleogene to the earliest Oligocene was essentially an ice-free period, whereas a marked drop in isotopic temperature occurred in the early Oligocene indicating a rapid increase in ice volume.

4. IMPLICATIONS FOR RESOURCE EXPLORATION

4.1 INTRODUCTION

In addition to climate, organic evolution, ocean currents and tectonic setting, changes in sealevel have played an important role in determining the distribution of environments favourable for resource accumulation. For example, marine economic deposits such as petroleum source rocks, phosphate, iron and manganese have been linked to zones of upwelling (e.g. Parrish & Barron, 1986) which are often associated with global sealevel highstands (e.g. Schlanger & Jenkyns, 1976). Terrestrial economic deposits (e.g. coal and petroleum source rocks, laterites, bauxites, evaporites) are, to a large extent, dependent on climate but they also require specific depositional conditions. It is beyond the scope of this report to explore the relationship between all the various sedimentary resources, sealevel and palaeoenvironmental setting. The following sections concentrate on implications for hydrocarbon resources.

It is widely believed that most of the world's oil reserves are sourced from marine mudstones rich in marine organic debris (e.g. Tissot & Welte, 1978). Most of Australia's hydrocarbon resources, however, are sourced from land-plant debris in sediments deposited in a variety of environments, ranging from fluvial to marine (Thomas, 1982). Almost all known hydrocarbon reservoir units in Australia are sandstones which were deposited in fluvial, fluvio-deltaic to paralic and shallow marine depositional environments. The temporal and spatial distribution of both marine and terrestrial depositional environments and their occurrence in relation to sealevel variations is therefore important for the prediction and delineation of areas for hydrocarbon exploration.

4.2 PALAEOENVIRONMENTS AND THE OCCURRENCE OF SOURCE AND RESERVOIR ROCKS IN THE PHANEROZOIC

Figures 14 to 17 show the distribution of palaeoenvironments throughout the Phanerozoic. Plotted against these charts are the global sealevel curves of Vail & others (1977b) and Haq & others (1987) respectively, and the Australian inundation curve. The environment distributions are shown as smoothed curves which connect values plotted at the midpoints of time slices; they therefore give only an approximation of the variations in area of environments with time. Known occurrences of source and reservoir rocks plotted on the right hand side of the charts are not comprehensive; they are selective and depict the more important occurrences. The source rock data are based on the detailed compilation of Haji-Taheri & Powell (1986). The plot of reservoir rock occurrences is based on compilations carried out during the BMR-AMIRA Palaeogeographic Maps Project.

Throughout the Phanerozoic, the greater part of present-day Australia was comprised of areas covered by unknown and unclassified environments (LEU), that is, environments unknown due to the lack of a stratigraphic record. Erosional environments (LEE) varied considerably through time, with increases in areas of erosion typically corresponding to marine regressions. For the Cambrian to Carboniferous, the marine inundation curve is fringed by very narrow zones of coastal and fluvial to lacustrine environments. Source rocks of the mid-Cambrian and Early Ordovician (e.g. in the Georgina Basin, and Canning Basin, respectively) accumulated in marine environments; they are typically associated with relative sealevel highstands. In the greater part of Australia, deposition during the Devonian was characterized by redbeds. Source rocks are only known from the Late Givetian to Frasnian Gogo Formation of the Canning Basin (Horstman, 1984), which was characterized by a zone of upwelling during this time (Parrish, 1982).

Permian source rocks typically contain terrestrial organic matter. In the western Australian basins, they accumulated in shallow marine to coastal environments, whereas the thick coal measure sequences of eastern Australia (e.g. Gidgealpa Group of the Cooper Basin) were deposited in fluvial to lacustrine environments. They are considered by some workers (e.g. Kantsler

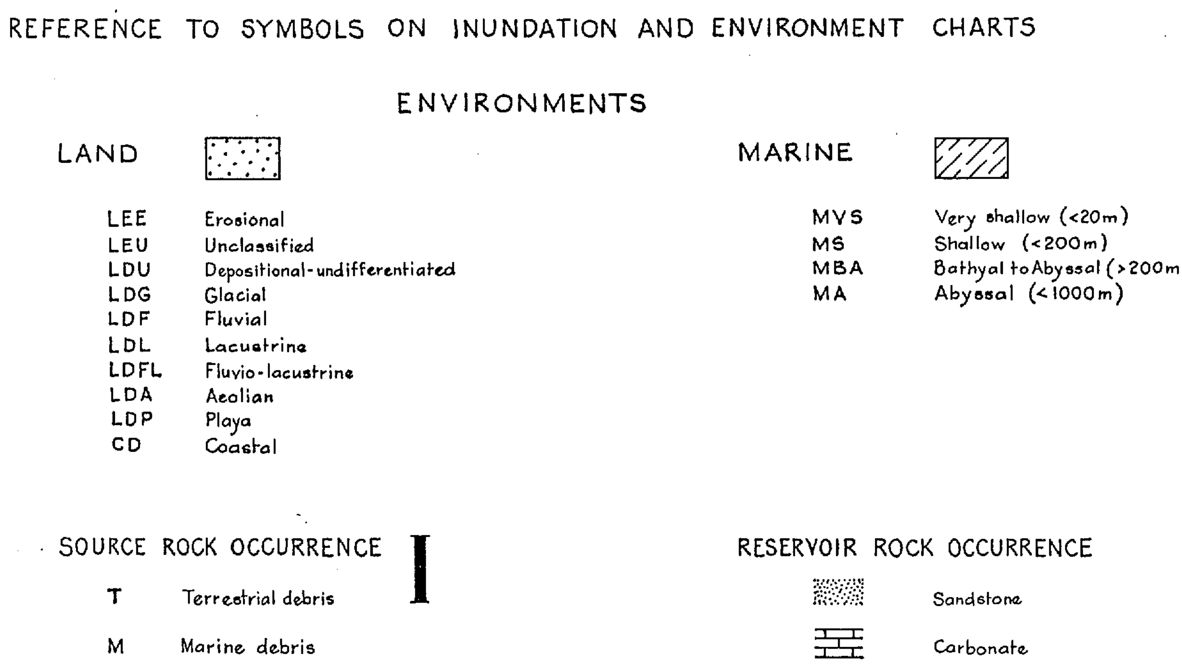


Figure 13: Legend for Figures 14 to 17.

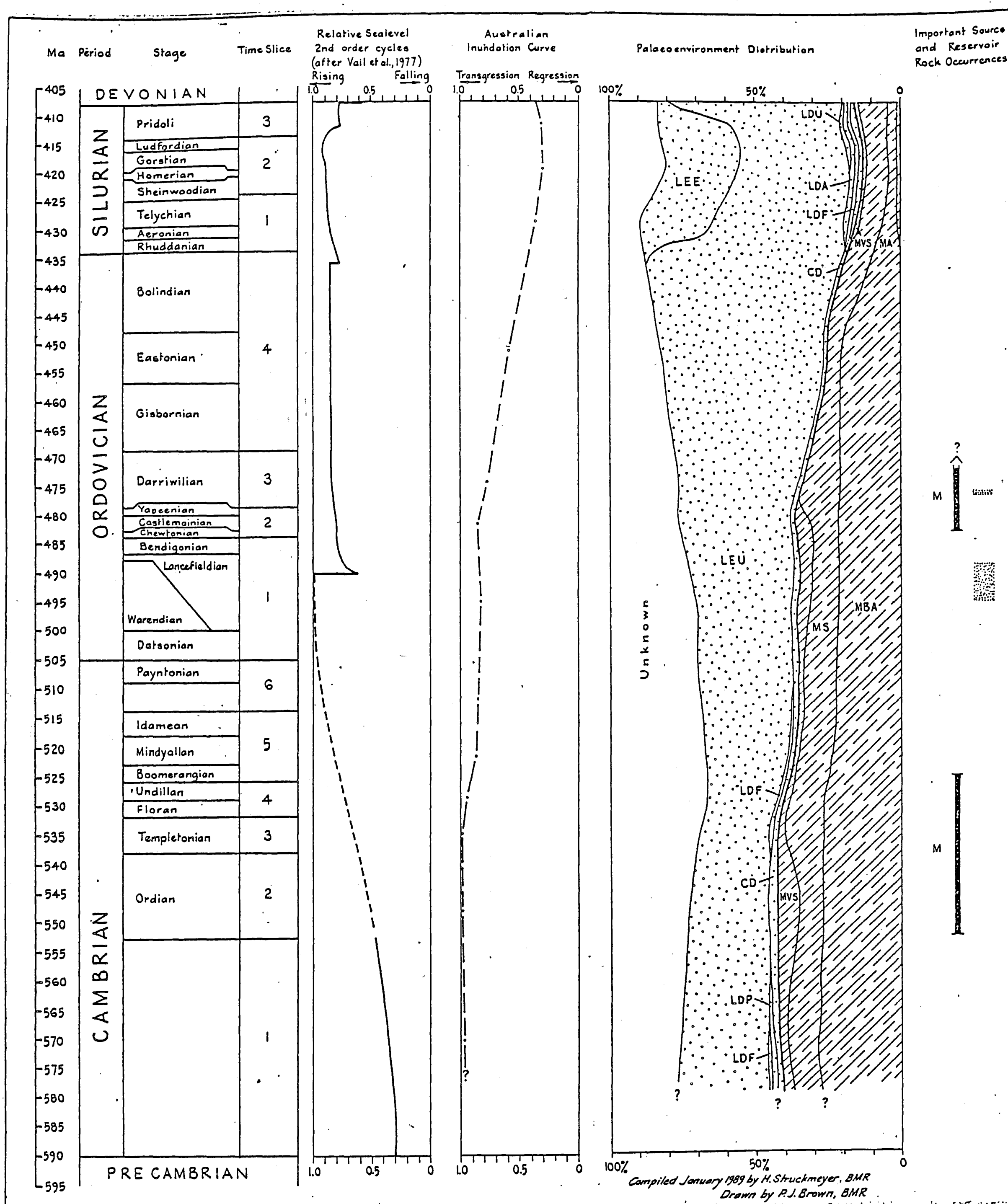


Figure 14: Palaeoenvironment distribution and relative sealevels during the Cambrian to Silurian.

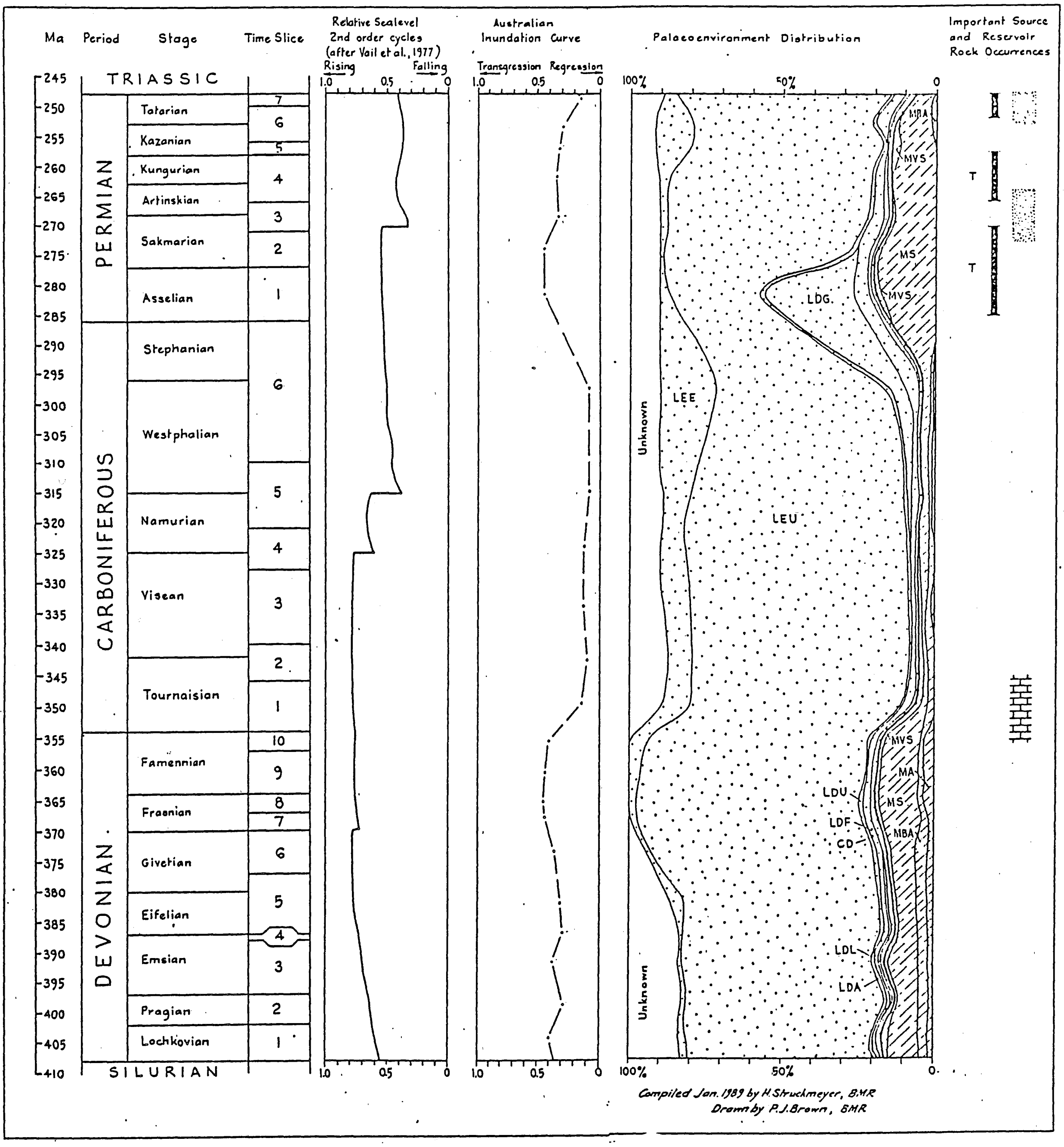


Figure 15: Palaeoenvironment distribution and relative sealevels during the Devonian to Permian.

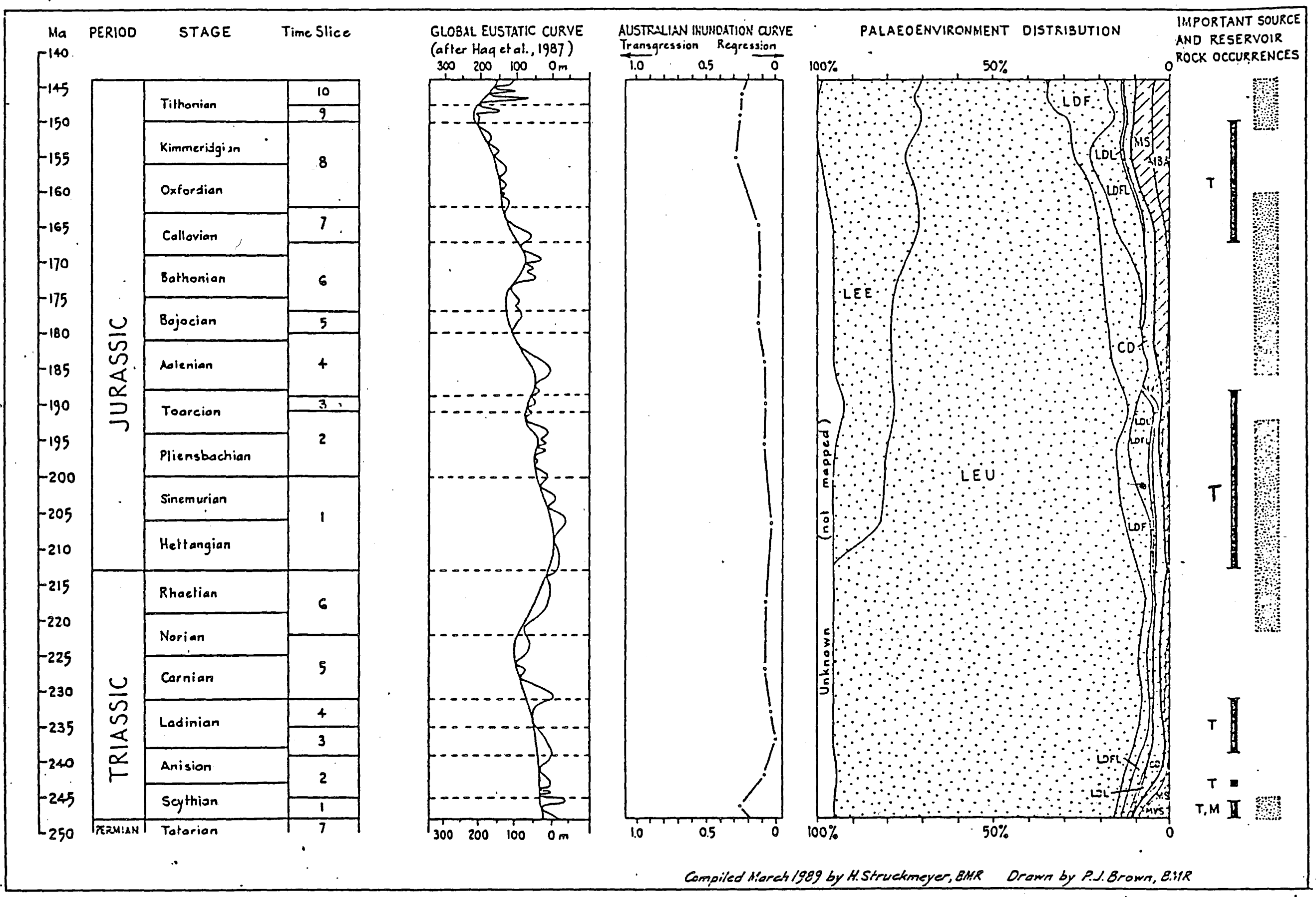


Figure 16: Palaeoenvironment distribution and relative and eustatic sealevels during the Jurassic to Triassic.

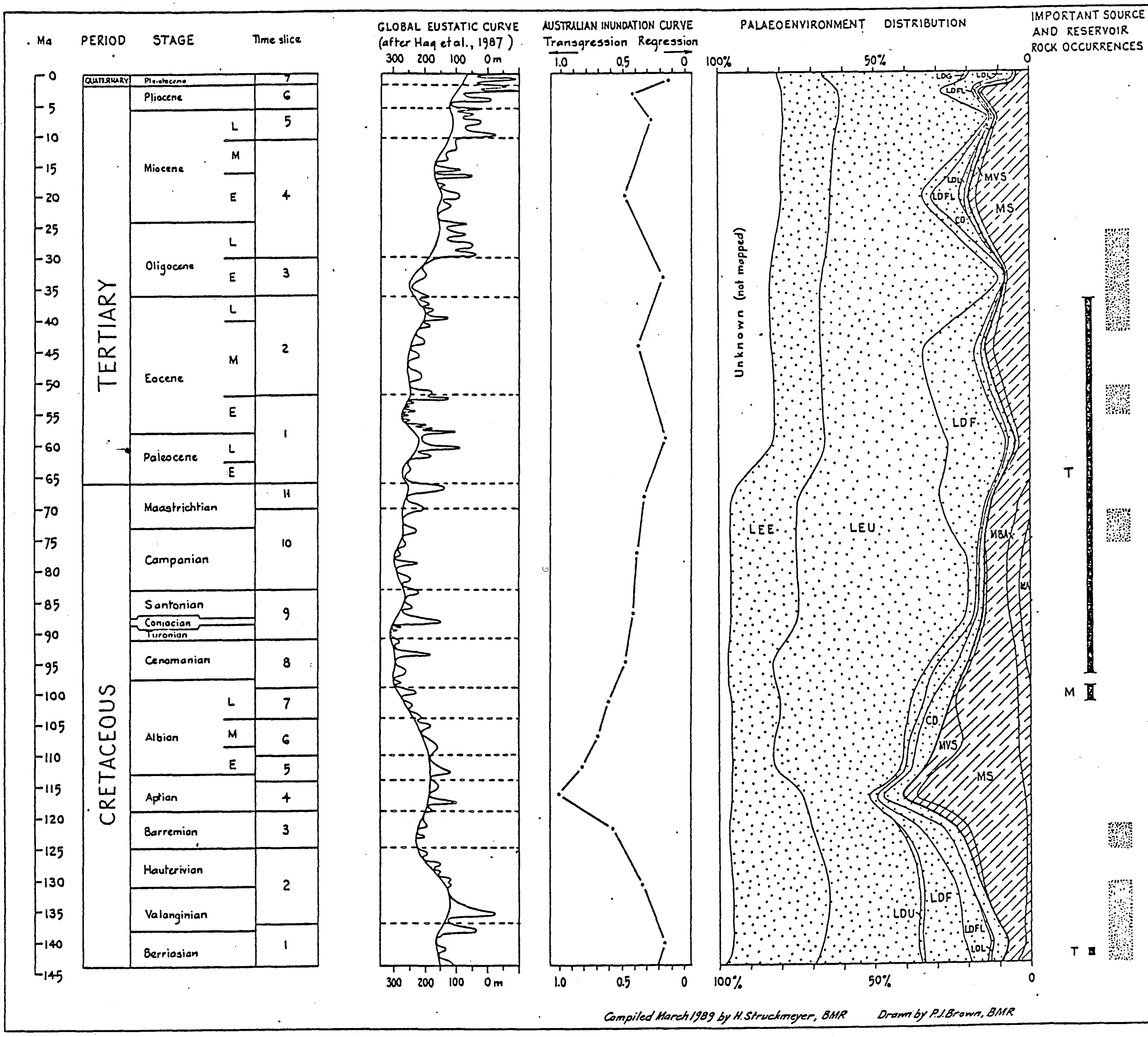


Figure 17: Palaeoenvironment distribution and relative and eustatic sealevels during the Cretaceous to Cenozoic.

& others, 1986; Alexander & others, 1988; Heath & others, 1989) to provide the source for many of the oil accumulations in the Cooper/Eromanga Basin. With the exception of Early to Middle Triassic source rocks deposited in the Perth and Carnarvon Basins, the Triassic generally contains no important source rocks. The Kockatea Shale (Perth Basin) contains organic matter derived from both marine organisms and land plants and was deposited in shallow marine environments. The Locker Shale and Mungaroo Formation (Carnarvon Basin) contain terrestrial organic matter only; they accumulated in marine and fluvio-deltaic environments respectively.

Good oil source rocks occur throughout the Jurassic, but the more important source horizons are present in Early and Late Jurassic sediments (e.g. 'basal Jurassic' and Birkhead Formation of the Eromanga Basin, Walloon Coal Measures of the Clarence-Moreton Basin, Cockleshell Gully Formation of the Perth Basin, and Late Jurassic shales of the Northwest Shelf). Haji-Taheri & Powell (1986) divided Jurassic source rocks into two groups, those that accumulated in marine environments along the western margin and those that accumulated in fluvial to lacustrine environments in eastern Australia. However, the authors stressed that in both groups the organic matter consists of plant-derived debris.

Source rocks are comparatively rare in Early Cretaceous sediments of Australia. They include the Murta Member of the Mooga Formation (Eromanga Basin) and horizons containing abundant organic matter in Otway Basin sediments of Berriasian and Aptian to early Albian age (Struckmeyer, 1988). The late Albian Toolebuc Formation was deposited over an extensive area of eastern Australia and contains significant amounts of marine organic matter. Late Cretaceous to Early Tertiary sediments are the source of the Gippsland Basin oil accumulations. They typically contain coal and carbonaceous shales deposited in mostly fluvio-deltaic environments.

The occurrence of known important source rocks in the Australian Phanerozoic suggests that source rocks deposited in both marine environments and fluvial to lacustrine environments accumulated preferentially during times of relative sealevel highstands. This trend is observable for the Palaeozoic as well as the younger sections. Exceptions to this trend occur in the Devonian and in the Aptian. These periods were characterized by high clastic input which may have resulted in low concentrations of terrestrial organic matter (Haji-Taheri & Powell, 1986). Unfavourable climatic conditions and the lack of a diverse flora may also have been responsible for the absence of major source sequences in the Devonian.

It is also interesting to note that the source rock occurrences correspond to highstands shown on the Australia-wide inundation curve and not necessarily to those of the global curves, unless there is correlation between the curves. Also, the degree of inundation appears to be of no major importance to source rock occurrence. For example, important source rocks accumulated during relative highstands in the Jurassic, a period of comparatively low overall inundation of the continent. The coincidence of high relative sealevel with the occurrence of source rocks in terrestrial environments appears to document the existence of a link between sealevel and depositional environments in non-marine basins far removed from the continental margin.

The distribution of reservoir rocks in the Australian Phanerozoic documents that reservoir accumulation occurs during both highstands and lowstands of relative sealevel. During transgressions and highstands, deposition of shoreline sand bodies occurred; for example, the Dongara Sandstone Member of the Kockatea Shale (Triassic 1, Perth Basin), the Windalia Sandstone Member of the Muderong Shale (Cretaceous 4, Barrow Sub-basin) and the Pacoota Sandstone (Ordovician 1, Amadeus Basin) (M.T. Bradshaw, pers. comm., 1989). Typical lowstand reservoir rocks include the lowstand fan Flag Sandstone (Cretaceous 2, Barrow Sub-basin) and perhaps some Late Jurassic sandstones of the Barrow-Dampier Sub-basin. Bodard & others (1986) emphasized the importance of sealevel changes on reservoir rock distribution in the Gippsland Basin Latrobe Group, where repeated transgressions and regressions caused the migration of barrier, strandplain and barrier-bar sandstones within a shorezone depositional system, as well as the occasional development of submarine channelling. The influence of relative sealevel on the occurrence of hydrocarbon reservoir rocks is more indirect than its influence on source rock accumulation: relative sealevel influences the distribution of palaeoenvironments and hence the type and geometry of reservoir sandstone bodies.

Times of major inundation also provide good reservoir sealing potential. For example, the deposition of marine shales and marls in the Gippsland Basin, which provide an extensive regional seal, occurred as a result of a major transgression during the Late Oligocene to Miocene (Brown, 1986), and Early Cretaceous shales deposited during the Aptian transgression are a regional seal for oil and gas reservoirs of the North West Shelf (Bradshaw & others, 1988).

4.3 VARIATIONS IN RELATIVE SEALEVEL AND PALAEOENVIRONMENT IN NON-MARINE BASINS

Changes in sedimentation patterns of fluvial systems over geologic time spans are determined by a number of variables including initial relief, structural setting, palaeoclimate, base level, and hydrology of the drainage system (Schumm, 1977). According to Powell (1875), sea level is the ultimate erosional base level toward which all streams tend to cut their beds. Variations in sealevel should therefore have an effect on the sedimentation patterns in fluvial systems of the hinterland. Recently, there have been some publications exploring the relationship between terrestrial sedimentation patterns in intracratonic basins and sealevel variations. For example, Exon & Burger (1981) correlated Jurassic to Cretaceous cycles of sedimentation in the Surat Basin with global sealevel changes postulated by Vail & others (1977b). They suggested that rapid falls in sealevel caused regional falls in erosional base level resulting in high energy fluvial deposition, whereas rising sealevels resulted in rising base levels causing a decrease in relief and depositional energy. O'Brien & Wells (1988) investigated controls on early to mid- Jurassic sedimentation in the Clarence-Moreton Basin and argued that, in some instances, sealevel may have controlled base level and therefore palaeoenvironments, but that tectonism exerted a major control.

A possible relationship between sealevel and non-marine palaeoenvironment can best be studied in the Eromanga, Surat and Clarence-Moreton Basins where sedimentation was terrestrial throughout the Jurassic. The basins were part of an extensive fluvial system draining into the proto-Pacific to the east of the present-day coast (Bradshaw & Yeung, in prep.).

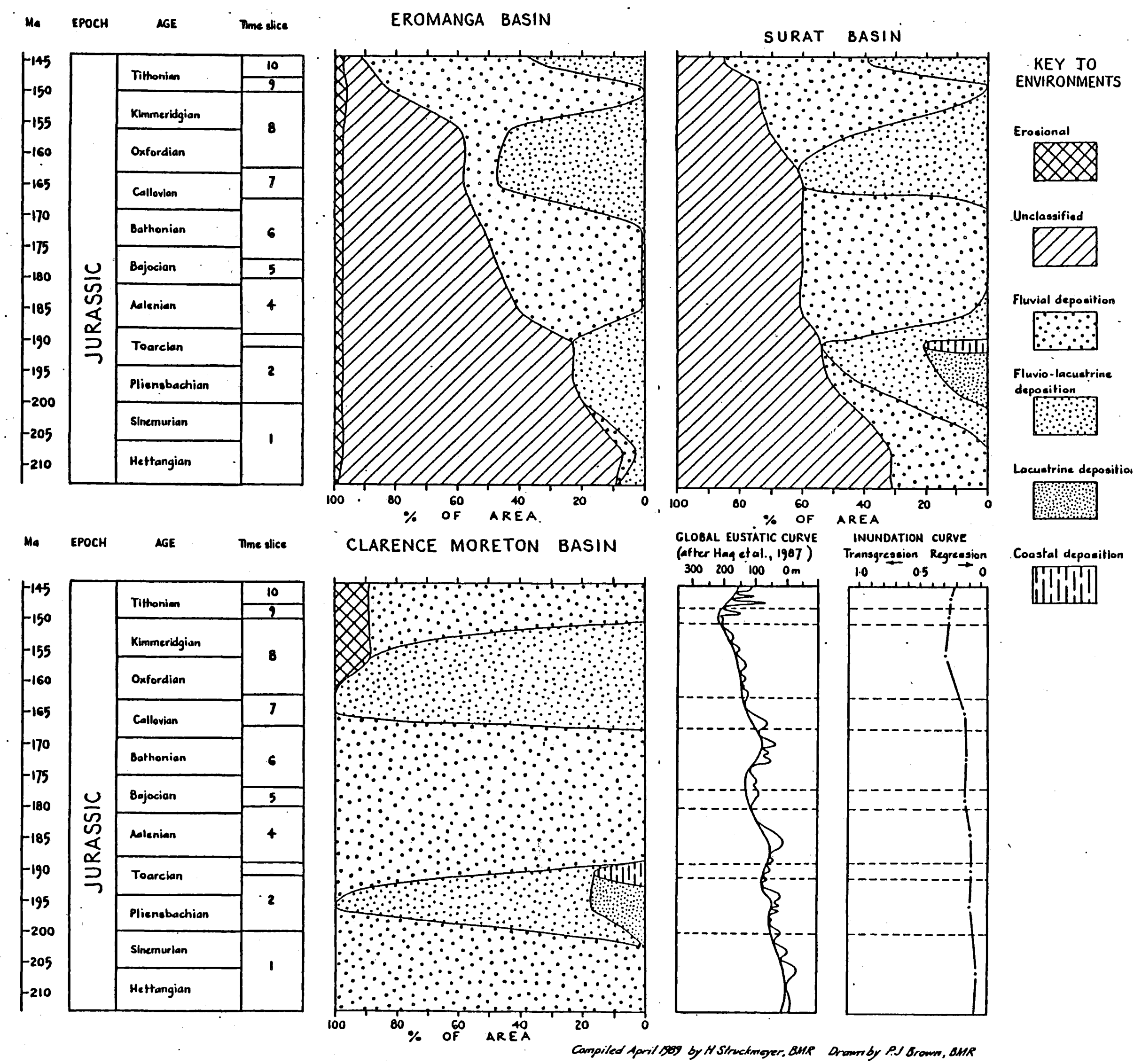


Figure 18: Jurassic palaeoenvironment distribution in the Eromanga, Surat and Clarence-Moreton Basins.

After a Late Triassic erosional event and subsequent subsidence (e.g. Kantsler & others, 1986), deposition in the Eromanga, Surat and Clarence-Moreton Basins commenced in mostly fluvial environments in the Late Triassic to Early Jurassic (Figure 18). Areas of fluvio-lacustrine and lacustrine environmentsincreased in the later part of time slice 1, culminating in TSJ 2 to 3 with some coastal deposition along the fringes of the eastern ocean occurring in the Surat and Clarence-Moreton Basins (TSJ 3). During this time source rocks accumulated in the fluvio-lacustrine environments (e.g. 'basal Jurassic', Poolowanna Beds). In all three basins, time slices 4 to 6 were again characterized by higher energy fluvial palaeoenvironments. During this time, prime hydrocarbon reservoir sandstones were deposited over the area (e.g. Hutton Sandstone). Fluvio-lacustrine deposition was again dominant during TSJ 7 to 8, a period during which the source rocks of the Birkhead Formation and Walloon Coal Measures accumulated. In the later part of TSJ 8 these environments were substituted gradually by fluvial environments and another phase of coarser clastic sedimentation occurred, mainly in TSJ 9. In the Clarence-Moreton Basin, environments remained fluvial, whereas fluvio-lacustrine conditions increased again in the Eromanga and Surat Basins in the latest Jurassic.

Figure 18 shows that changes in sedimentary environments from higher energy fluvial to lower energy fluvio-lacustrine and lacustrine environments coincide in the three basins depicted. The low energy fluvio-lacustrine depositional environments in TSJ 2/3 and 7/8 are likely to be the result of a rise in base level. The Australian inundation curve shows that the TSJ 2/3 episode corresponds to a minor transgression in TSJ 2 and to a eustatic highstand according to the curve of Haq & others (1987). The Late Jurassic episode also occurs during a transgressive phase depicted on the inundation curve; it does not correlate well with the eustatic curve which shows the Jurassic highstand occurring in TSJ 9, although sealevel was rising through the Kimmeridgian to peak in the early Tithonian. The mid-Jurassic transgression, which is recognizable on both the inundation curve and the eustatic curve, appears to have had no effect on sedimentary environments in eastern Australia. This may indicate that the possible result of a sealevel rise was counteracted by a tectonic event. For example, O'Brien and Wells (1988) argued that this period in the Clarence-Moreton Basin was characterized by tectonic rejuvenation and increased subsidence. Other causes for the Jurassic sedimentation patterns

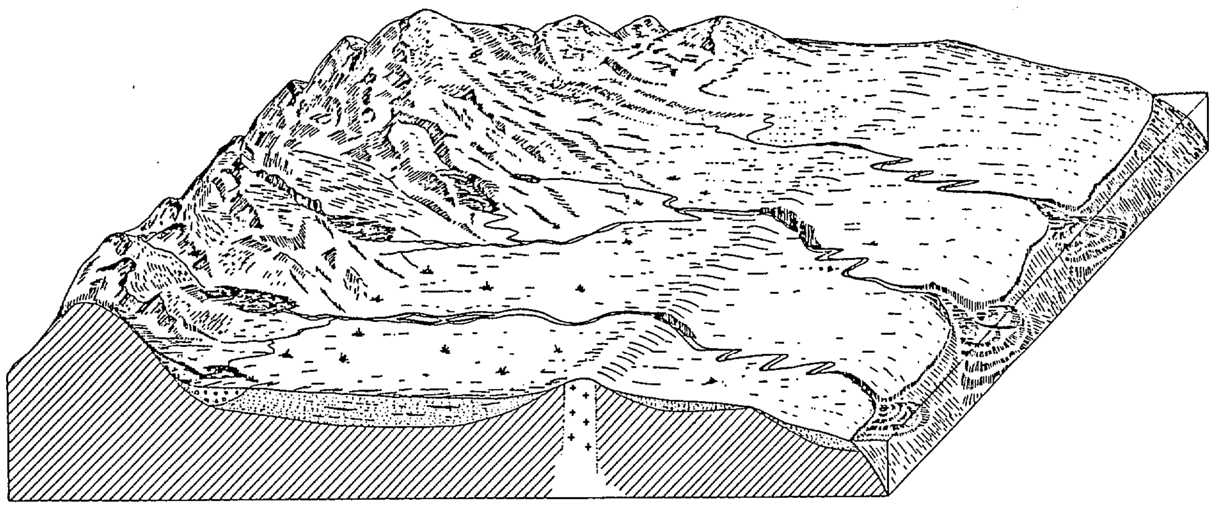


Figure 19: Schematic representation of depositional environments during a relative sealevel lowstand.

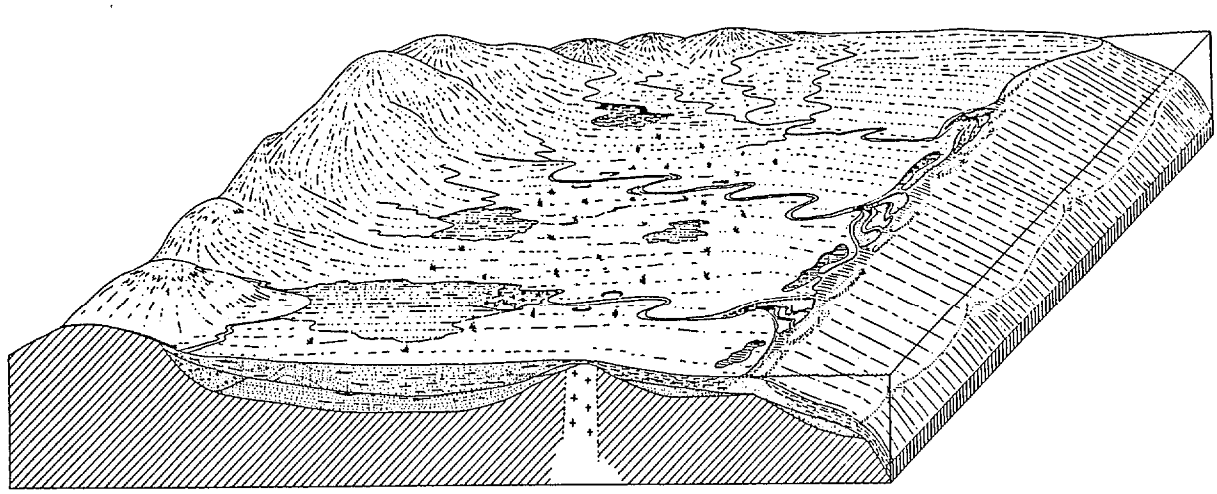


Figure 20: Schematic representation of depositional environments during a relative sealevel highstand.

in the basins examined may include intermittent changes in the rate of subsidence and global climate variations. The latter can probably be excluded as the warm-temperate climate remained relatively stable throughout the Jurassic (Frakes, 1979). Watts (1987) suggested that dammingof the drainage system by volcanic activity in the east caused the change in palaeoenvironment from TSJ 4-6 to TSJ 7/8.

Thus, although some palaeoenvironment data do not correlate with relative sealevel changes, it is suggested that depositional environments in Jurassic intracratonic basins of eastern Australia were at least partly controlled by sealevel. The block diagrams in Figures 19 and 20 show two simplified models for depositional environments in the Eromanga, Surat and Clarence-Moreton Basins during a relative sealevel lowstand and a relative sealevel highstand. During the lowstand (e.g. Time Slices 4 to 6 - Hutton Sandstone) environments were characterized by a fluvial landscape with alluvial fans, braided rivers and occasionally inundated floodplains. The highstand (e.g. Time Slices 2/3 and 7/8 - Poolowanna and Birkhead Formations) depicts a landscape with considerably lower relief, meandering rivers and vast floodplains dominated by lacustrine environments.

Further examples that could be used for exploring the relationship between terrestrial deposition and sealevel are the Permian to Triassic sequences of the Cooper and Pedirka Basins, but the tectonic activity in these basins during this time probably obscures the sealevel signature. However, the Triassic TS 1 and the Permian TS 4 (Cooper Basin) transgressions correspond to increased percentages in fluvio-lacustrine to lacustrine environments. Further back in the Palaeozoic, comparison between environment and sealevel becomes problematic because of difficulties with biostratigraphic correlation. Also, most Palaeozoic basins were dominated by marine deposition.

In conclusion, it is suggested that there is a relationship between sealevel and depositional style in both passive margin basins and intracratonic basins. In the Australian Phanerozoic, favourable environments for source rock accumulation typically developed during times of relative sealevel highstands. Interpretations of relative changes in sealevel therefore have predictive capability for resource exploration.

5. SUMMARY AND DISCUSSION

Seventy palaeogeographic maps produced during the BMR-AMIRA Palaeogeographic Maps Project were used as the data base for the construction of Australian inundation curves. Percentages of total marine environment were plotted proportionally against geologic time at the mid points of 70 time slices from the Cambrian to Cainozoic. The resulting curve gives a record of relative sealevel changes during the Phanerozoic of Australia. Limitations to the method are given by the number and length of time slices and the accuracy of the palaeogeographic maps.

The most extensive flooding of the Australian continent occurred in the early mid-Cambrian and the Early Cretaceous with further highstands occurring in the Early Ordovician, Late Devonian, Early Permian, Late Jurassic, Eocene, Early Miocene, and Pliocene. Periods of relative sealevel lowstand were present in the Silurian, Carboniferous, Triassic and Early to mid-Jurassic. Some relative lowstands and highstands depicted on the Australian inundation curve correlate with those on published sealevel curves for the Phanerozoic (e.g. Vail & others, 1977b; Hallam, 1984), for example, the Late Devonian highstand, the Triassic/Jurassic lowstand, the Late Jurassic highstand and the transgressions and regressions in the Cainozoic. These events probably have eustatic origin. In some instances, however, considerable differences are present between the Australian curve and published curves, for example, the Late Ordovician regression, the Early Permian highstand and the Aptian highstand shown on the Australian curve are not recognizable on the published curves. Some of the disagreements between the curves can be ascribed to difficulties in correlating the time scales used or to the lack of biostratigraphic control for some geologic periods, particularly, the older Palaeozoic periods. However, they could also indicate times where movements of the coastline depicted on any of the curves were not due to eustasy changes but to tectonic movements (including glacio-isostasy), which in turn, could overprint, reverse or enhance a eustatic event.

Marine flooding curves for individual basins for each geological period were compiled and then compared with the Australian inundation curve and published sealevel curves for these periods, in order to provide a more detailed record of relative sealevel changes in the Australian region and to explore some of the problems involved.

For most periods, marine flooding curves for basins generally correspond to the Australia-wide curve. Disagreements are likely to reflect local to regional tectonic movements or changes in sedimentation rates. Local to regional tectonic events can also subdue, enhance or dominate the shape of the Australian curve and, in some cases, they are probably significant enough to explain divergences between published curves for the geologic periods concerned and the Australian curve. However, these divergences may also reflect tectonic events in the region the published curve originated from, because the latter would also contain regional bias.

The most obvious divergence of the Australian curve from published curves of mostly the northern hemisphere is present in the Cretaceous, highlighting some of the problems relating to the distinction of tectonic from eustatic events. The Australia-wide curve is dominated by the Aptian inundation of approximately half the Australian continent and the following retreat of the sea from this area whereas, on the published curves, the eustatic high for the Cretaceous occurs in the Late Cretaceous. Comparison of marine flooding curves for various basins shows that the shape of these curves depends very strongly on the tectonic setting of the basin during a particular time. Flooding curves for intracratonic basins from various areas of Australia all show a major regression during the Albian. The coincidence of this event requires a mechanism that would effect the entire continent, such as epeirogenic uplift. On flooding curves for basins from the continental margin the Aptian event is typically subdued and the highest percentage of marine flooding occurred in the Late Cretaceous.

The marine flooding curves indicate that Australia's passive margin basins of Jurassic to Cainozoic age typically follow a pattern of initial flooding after breakup and then increasing transgression until, apparently, a tectonically more stable phase is reached and eustasy rather than tectonic movement becomes the more important influence on sedimentation. The curves for the continental margin basins correlate relatively well with the eustatic curve of Haq & others (1987), whereas those for intracratonic and very young continental margin basins show little correlation; this may be a reflection of a bias of the Haq & others' curve towards passive continental margins. As both increasing rates of seafloor spreading and epeirogeny have been quoted as causes for eustasy fluctuations, the decision when to call a relative sealevel event eustatic is problematic. Therefore, evaluation of eustatic sealevel changes should not be restricted to basins with similar tectonic settings.

Most of Australia's oil reserves were sourced from land-plant debris in sediments deposited in a range of terrestrial to marine environments. The occurrence of known hydrocarbon source rocks throughout the Australian Phanerozoic indicates that they accumulated preferentially during relative sealevel highstands. Important reservoir facies developed during both lowstands and highstands of relative sealevel, and the type and geometry of sandstone reservoirs was also influenced by sealevel. Investigation of the relationship between relative sealevel and terrestrial deposition in Jurassic intracratonic basins of eastern Australia suggests that depositional environments were at least partly controlled by relative sealevel. Although exceptions are present, periods characterized by relatively low energy fluvio-lacustrine to lacustrine environments are typically associated with relative sealevel highstands, whereas higher energy fluvial environments occur during relative sealevel lowstands. Relative sealevel changes therefore have a predictive capability for hydrocarbon exploration in both terrestrial and marine sequences.

The compilation of areas of marine flooding from 70 palaeogeographic maps has provided a first order relative sealevel curve for the Australian Phanerozoic. The curve shows a combination of the effects of sealevel, sediment supply and local and regional tectonic movements. Comparison of the Australia-wide curve with marine flooding curves for individual basins shows that, in many cases, local and regional tectonic events dominate the Australia-wide curve. The curve therefore shows a general trend, but for assessment of relative sealevel change for given areas, and its implication for depositional style, the basin curves are considered to be more useful. More detailed studies of geologic periods and areas important for hydrocarbon exploration are planned, particularly where the Australian curves show significant divergence from global sealevel curves.

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