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Australia's buoyancy inherited from Gondwanaland[1]

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In company with the other components and continental successors of the Neoproterozoic to Mesozoic Gondwanaland supercontinent, Phanerozoic Australia has a buoyant cratonic platform characterised by non-marine facies, in contrast to the marine facies of the components of depressed Laurasia. As a supercontinent, Gondwanaland lasted much longer than Laurasia, and was therefore hotter from its more effective insulation of internal heat. Moreover, the Pan-African orogenic cycle, confined to Gondwanaland, augmented the heat supply, and I postulate that Pan-African heat generated a permanently buoyant lower crust by mafic underplating. A crustal layer in the Australian Proterozoic shield with subhorizontal reflectors and velocity (V_p) > 7.5 km s^{-1} is interpreted as the product of mafic underplating beneath latest Neoproterozoic flood basalt. The Pan-African terrane in East Africa also contains evidence of mafic underplating, and most of Gondwanaland (but not Laurasia) was affected by terminal Pan-African (0.5 Ga) uplift and cooling. In equivalent Late Cretaceous and Late Ordovician stages of the 400 m.y. Pangean supercycle, the Australian (and possibly the South American) platform deviated from the global norm by rising faster than eustatic sea level. In Australia, plate boundary events — steeper subduction, mafic underplating of a lower plate along a divergent back-arc boundary — explain uplift in the east, but not that in the west, which relaxed to its natural buoyant state.

Introduction

Fischer (1984) and Veevers (1990, 1994) interpreted the first-order features of the sea-level curve (Vail et al. 1977) as due to the two states of continent and ocean that alternate in a 400 m.y. supercycle:

(1) in the dispersed state, a long mid-ocean ridge displaces water upward to flood the many continents which have low-lying extended margins and low mean elevations; and

(2) in the Pangean state, a short mid-ocean ridge combines with shorter low-lying extended margins to produce an emergent Pangea.

Anderson's (1982) recognition of the Atlantic–African geoid high as a relic of Triassic Pangea pointed to heat generated in Pangea as the driving force of the supercycle. Authors such as Gurnis (1988) elaborated possible deep-seated mechanisms. Here I interpret the difference in buoyancy between Gondwanaland and Laurasia as due to preferential underplating of the lower crust of the long-lived Gondwanaland, and provide cogent information from Australia.

Flooding of the continental platform

From a line of descent through Gondwanaland, Australia and its siblings have inherited a buoyant lithosphere, indicated by the small area of the platform covered by the sea (Fig. 1; Veevers 1995). The Gondwanaland data come from Africa, Arabia, Indostania, South America (Ronov 1994), and Australia (BMR Palaeogeographic Group 1990, modified here).

In Australia, uncertainties about areas covered by the Palaeozoic sea in the present offshore Tasman Fold Belt System and New Guinea were avoided by excluding these areas from consideration. Accordingly, the area of the sea covering the continental platform was measured within the bounds of the present coastline of the mainland, extended to Tasmania from the Permian, and on the eastern margin from the Cainozoic shelf edge and the Cretaceous and older magmatic arc or orogen.

Except for an overlap in the Late Silurian (S2 in Fig. 1) and Early Devonian (D1), the curves of platform areas flooded by shallow seas (Fig. 1C) grossly parallel each other, but the larger area of Gondwanaland minus Antarctica (G in Fig. 1C; 53×10^6 km^2) has only half the area of the sea over the smaller Laurasia (L; 43×10^6 km^2); the percentage area flooded on each supercontinent has the same trend: G ranges from 2 to 24 per cent, and L from 6 to 46 per cent. The first-order curves of flooded areas also grossly parallel the number of continents (Fig. 1D), in sympathy with the curve of global sea level (Figs. 1A, 2).

Departures in Australia (Fig. 1A) from the sea-level curve are Australian peaks in Early/Middle Cambrian (C1/2; 520 Ma) and Early Ordovician (O1; 480 Ma) times versus Late Ordovician (O3; 450 Ma) time, and in Aptian (K1; 116.5 Ma) versus Campanian (K2; 80 Ma) time. An explanation of these departures is attempted below.

The contrast in the size of the flooded areas in Australia (present land area 7.7×10^6 km^2) and South America (17.8×10^6 km^2) compared with North America (22.0×10^6 km^2) is extreme, in particular during the Gondwanan (Carboniferous through Jurassic) interval of negligible flooding. For interior sites in Australia (dotted circle in Fig. 3A) and in the Amazon Basin of South America, and for mid-continental North America, the total intervals covered by the sea (heavier shading in Figs 1A, B) provide the same contrast: Australia for 70 m.y., or 13 per cent of the 544 m.y. period surveyed; South America for 85 m.y., or 16 per cent, and North America for 275 m.y., or 51 per cent.

This fundamental difference in wetness is exemplified by the distribution of marine carbonate: major in Laurasia, minor in Gondwanaland. Neoproterozoic and Phanerozoic marine platforms in all but high latitudes are characterised, if not dominated, by carbonate sediment, and non-marine platforms by siliciclastic sediment. Abundant marine carbonate in the almost continuous Neoproterozoic and Phanerozoic sections of Laurasia means that studies of stable isotopes in Laurasian rocks have been conducted almost exclusively on carbonate; in Australia, where carbonate is only intermittent, such studies rely on the kerogen preserved in Neoproterozoic (e.g. Calver 1995) and Permian (e.g. Morante 1995) siliciclastic rocks.

Pangean supersequence

Pangean tectonics developed through the following ideas:

- Holmes (1931) proposed monsoon-like convection currents from the juxtaposition of ocean floor and radioactive continental blocks.
- Anderson (1982) interpreted the present positive geoid as a relic of Triassic Pangea.
- Gurnis (1988) made numerical simulations of large-scale mantle convection and the aggregation and dispersal of supercontinents.
- Veevers (1990, 1994) found evidence for a 400 m.y. period of Pangean tectonics from the distinctive Pangean supersequence deposited on the supercontinental platform since 320 Ma (cycle A), earlier from 720 Ma (cycle B), and initially, from 1120 Ma (cycle C).

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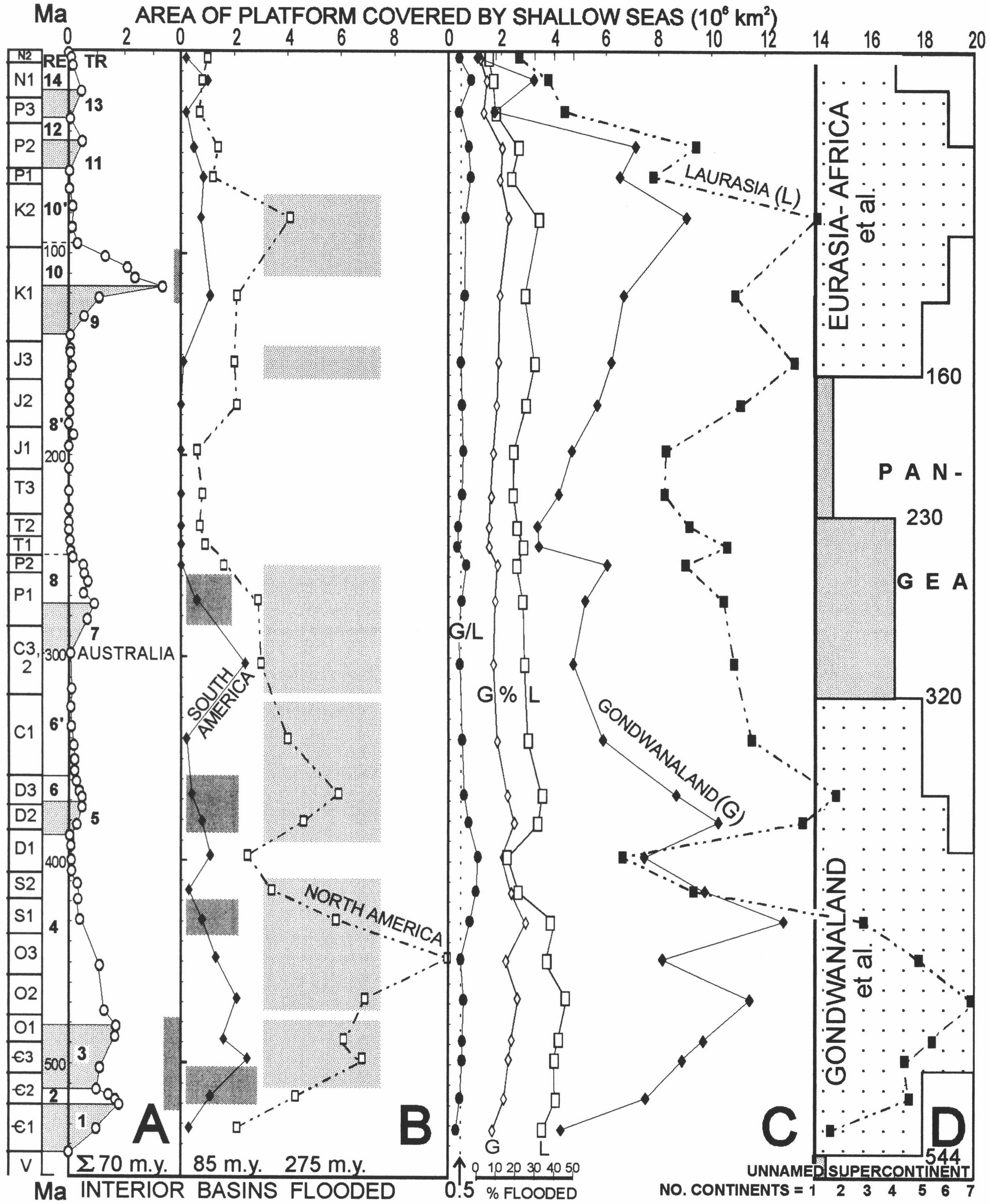


Figure 1. Area of platform covered by shallow seas during the Phanerozoic eon. A: Australia, 70 intervals (from BMR Palaeogeographic Group 1990) grouped in alternately shaded transgressions (TR: odd numbers, 1–13) and unshaded regressions (RE: even numbers, 2–14; including almost total exposure — 6', 8', 10'); dark shading indicates time intervals (total = 70 m.y.) of shallow seas in Georgina–Eromanga basin (circled area in Fig. 3A). B: South America and North America, 28 intervals (from Ronov 1994) representing shallow seas in three Brazilian cratonic basins (Soares et al. 1978) for a total of 85 m.y. and in central mid-continental United States (Bunker et al. 1988) for 275 m.y. C: Laurasia and Gondwanaland (Ronov 1994, modified by Australian data in A) and their ratio (G/L); percentage area flooded (scale below) is shown by open symbols. D: number of continents (scale below), from single Vendian (V) 'unnamed supercontinent' of Dalziel et al. (1994) through Gondwanaland et al. (as in Fig. 2) to initial Pangea at 320 Ma, rifting from 230 Ma, and breakup at 160 Ma to form Eurasia–Africa et al. (Scotese & Denham 1988; Veevers 1990). Diagram from Veevers (1995), but modified to show the Early Silurian (Llandovery) sea covering a minimum area of 0.33×10^6 km^2 in the Carnarvon Basin (represented by the middle part of the Ajana Formation; Gorter et al. 1994) and in the Canning Basin (represented by the parts of the Sahara Formation preserved after the Prices Creek Movement; Kennard et al. 1994, p. 662; Romine et al. 1994).

Gondwanaland inheritance

Veevers (1995) asserted that, because the supercontinent Gondwanaland lasted much longer than Laurasia, it was therefore hotter from its more effective insulation of internal heat and its own production of heat from radioactivity. Moreover, the Pan-African orogenic cycle, confined to Gondwanaland, augmented the heat supply. Both effects possibly generated a permanently buoyant lower crust by underplating, revealed today by a high-velocity ($V_p > 7.5$ km s^{-1}) lowermost crust.

Evidence of underplating of this age in Australia is found in the area south of the AUS 2 (Tennant Creek–Mount Isa) traverse, under the Georgina Basin. Here the lower crust has a $V_p = 7.53$ km s^{-1} (Rudnick & Fountain 1995), and contains short discontinuous vertical seismic reflection horizons, which Finlayson & Mathur (1984) interpreted as the effects of mafic underplating during one or more phases of extension. Another area of high-velocity ($V_p = 7.61$ km s^{-1}) lowermost crust is the Nullarbor Plain (AUS 3 traverse; Finlayson 1982).

The Georgina Basin contains the late Vendian (ca 570 Ma) 500 m thick tholeiitic Antrim Plateau Volcanics, which cover an area of 400 000 km^2. Together with the coeval tholeiitic Table Hill Volcanics, which cover an area of 50 000 km^2 (Veevers 1984, p. 282), they have a total preserved volume of 0.1×10^6 km^3. Xenoliths are unknown, probably because the geochemistry of the basalt (Bultitude 1976) indicates its unsuitability for sampling deep layers (S.Y. O'Reilly, Macquarie University, personal communication 1995). I postulate that the basalt is the surface expression of a lower crustal mafic underplate represented by the high-velocity zone in the lower crust in the AUS 2 and 3 traverses, and that the mafic underplate provided long-term buoyancy during subsequent Phanerozoic time. Buoyancy would have been effected by the injection of a 5 km thick mafic layer of density 3.0 t.m^{-3} displacing 3.3 t.m^{-3} mantle to induce an isostatic rise of 0.5 km.

Lower layers in South Australia at the eastern end of the AUS 3 (Nullarbor) traverse are dated by the U–Pb method on zircon from xenoliths; the data indicate episodic heating events at 1.6 to 1.5, 0.78, 0.62, and 0.33 Ga (Chen et al. 1994). The Neoproterozoic (0.78 and 0.62 Ga) events are within the 0.95–0.45 Ga Pan-African thermotectonic cycle (Rogers 1993). Evidence of Neoproterozoic mafic underplating is also preserved in the lower crust of Sudan and East Africa (Stern 1994). The many 0.5 Ga dates in the Australian platform belong to the terminal Pan-African event: 'Widespread thermal rejuvenation, shear zone activation and anorogenic magmatism peaked at 0.5 Ga and affected most of West Gondwana and localised regions of Gondwana' (Unrug et al. 1994, p. 440); they were followed by rapid uplift and cooling by denudation. Most of Gondwanaland (but not Laurasia) was affected by this terminal Pan-African (0.5 Ga) uplift and cooling. These and other contrasts with Laurasia are shown in Table 1.

Pangean cycle A tectono-sedimentary stages of subsidence

The Pangean stages (Fig. 2, columns X [encircled numbers 1 to 5] and XI [sequences on the Gondwanaland platform]) are as follows:

- *stage 1 (320–290 Ma)*, represented on the platform by a stratigraphic gap or lacuna, reflects the initial accumulation of heat beneath the Pangean insulator and thermal uplift;
- *stage 2 (290–230 Ma)*, represented by the epi-Carboniferous to mid-Triassic early Gondwana sequence and equivalents, marks the local thinning of the Pangean crust to form broad basins or sags and, locally (on orogens), bimodal volcanic rifts generated by the initial withdrawal of heat from beneath Pangea;
- *stage 3 (230–160 Ma)*, represented by the mid-Triassic (Carnian) to mid-Jurassic rift sequence, reflects a faster withdrawal of heat and concomitant crustal thinning along the incipient rifted margins of Pangea;
- *stage 4 (160–85 Ma)*, represented by the mid-Jurassic to mid-Cretaceous drift sequence, reflects the wholesale loss of Pangean heat by fast sea-floor spreading; and
- *stage 5 (85 Ma to present)*, represented by the Late Cretaceous and younger drift sequence, reflects a slower loss of heat from the depleted Pangean heat store.

Stages 3 to 5 (boxed numbers) of the previous cycle are sketched in column X of Figure 2.

Comparative Pangean episodes 200–0 Ma and 600–400 Ma

Figure 3 shows in plan the Cretaceous transgressive–regressive episode (events 9, 10, and 10' in Fig. 1A) in Pangean cycle A, and Figure 4 the early Palaeozoic events (1–4 in Fig. 1A) of the preceding 400 m.y. cycle B. These and other events are listed in Table 2 and shown in Figure 5, the time–space diagrams of 200–0 Ma and, offset 400 m.y., 600–400 Ma. The episodes constitute parts of Pangean stages 3 (extension II), all of 4 (fast sea-floor spreading), and parts of 5 (slow sea-floor spreading; Fig. 2, column X) during the transition from Pangea to the dispersed continents.

Gross geography

The Cretaceous episode (Fig. 3) involved an Australian platform wider than the initial state in the Cambrian, owing to the Palaeozoic accretion east of the Tasman Line. The area available for flooding was therefore greater, and the northern and western passive margins became open to the ocean, so that the sea encroached from the north and west as well as

Table 1. Contrasting lithospheric features of Gondwanaland and Laurasia–Eurasia.

Character	*Gondwanaland*	*Laurasia–Eurasia*
Time span	1100–160 Ma	320–160 Ma
Duration as a supercontinent	1000 m.y.	< 200m.y.
Elevation	high	low
Facies	non-marine[a]	marine[b]
Terminal Pan-African event		
Peak K–Ar date	500 Ma	–
Oldest apatite fission-track date	500 Ma	1200 Ma
(A. Gleadow, La Trobe University, personal communication 1995)		(Pan-African event not registered here)
700–500-Ma tectonic events		
Intensity	momentous: Pan-African	slight
Lowermost crustal layer $V_{p(c)}$ ~7.5 km s^{-1} (Veevers 1995, fig. 3)	?common	?rare
Mechanism	mafic underplating	–

[a] Exemplified by rare, intermittently deposited carbonate.
[b] Exemplified by common, almost continuously deposited carbonate.

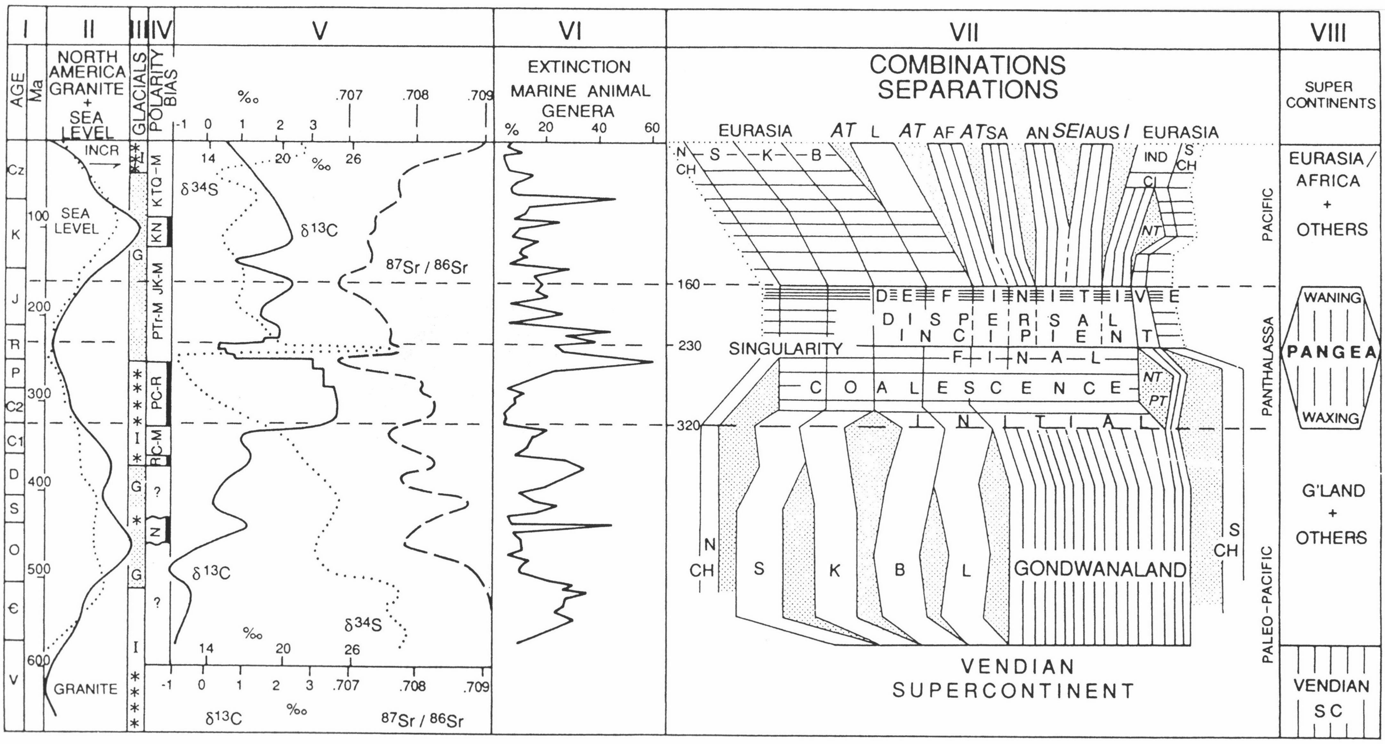


Figure 2. Phanerozoic sedimentary and tectonic indices, combinations and separations of the continents and oceans, supercontinents, flood lava, the Pangean heat anomaly, platform sequences, flooded area, and extension/shortening events, from a modified and augmented

Columns I and XV: **Timescale (Palmer 1983) with the Permian–Triassic boundary changed from 245 to 250 Ma (Veevers et al. 1994a). The Vendian/Cambrian, now regarded as 544 Ma, is referred to its previously accepted age of 570 Ma.**

Column II: **Solid line = ages of North American granites; dotted line = sea level (Fischer 1984).**

Column III: **Glacial occurrences (asterisks) with alternating ice-house (I) and greenhouse (G) states (Fischer 1984); the ice-house/greenhouse boundary is placed at the Permian–Triassic boundary.**

Column IV: **Magnetic polarity bias — N, normal; R, reversed (both with heavy bar); M, mixed (Harland et al. 1990).**

Column V: **Solid line = $\delta^{13}C$ in carbonate, and dotted line = $\delta^{34}S$ (Holser et al. 1988); broken line = $^{87}Sr/^{86}Sr$ (Koepnick et al. 1988).**

Column VI: **Percentage extinction for marine animal genera — < 260 Ma (Raup & Sepkoski 1986), > 260 Ma (Sepkoski 1992).**

Column VII: **Continental and oceanic combinations and separations (after Briden et al. 1974; Ziegler et al. 1979; Bond et al. 1984; and Sengor 1984). Gondwanaland and subsequent fragments marked with vertical and subvertical lines, Pangea and Eurasia with horizontal lines, and rift oceans with stipple; dotted lines alongside Eurasia join on either side. Continents: AF, Africa; AN, Antarctica; AUS, Australia; B, Baltica; CI, Cimmeria; IND, India; K, Kazakhstania; L, Laurentia; N CH, north China; S, Siberia; SA, South America; S CH, south China. Oceans (italicised letters): AT, Atlantic (north, central, south); I, Indian; NT, neo-Tethys; PT, paleo-Tethys; SEI, southeast Indian.**

Column VIII: **Supercontinents (vertical lines), large continents and others.**

Column IX: **Late Palaeozoic and Mesozoic flood lavas: A, European (Wopfner 1984; Ziegler 1988) and eastern Australian (Veevers 1984); B, Siberian traps (Renne & Basu 1991); C, Amazon (Mosmann et al. 1986); D, Karoo (Bristow & Saggerson 1983); E, Transantarctic and Tasmanian (Kyle et al. 1981; Schmidt & McDougall 1977); F, Serra Geral (Schobbenhaus 1984); G, Pacific ridge-crest (Watts et al. 1980); H, Rajmahal (Baksi 1988), J, Pacific mid-plate (Schlanger et al. 1981); K, Deccan (Jaeger et al. 1989).**

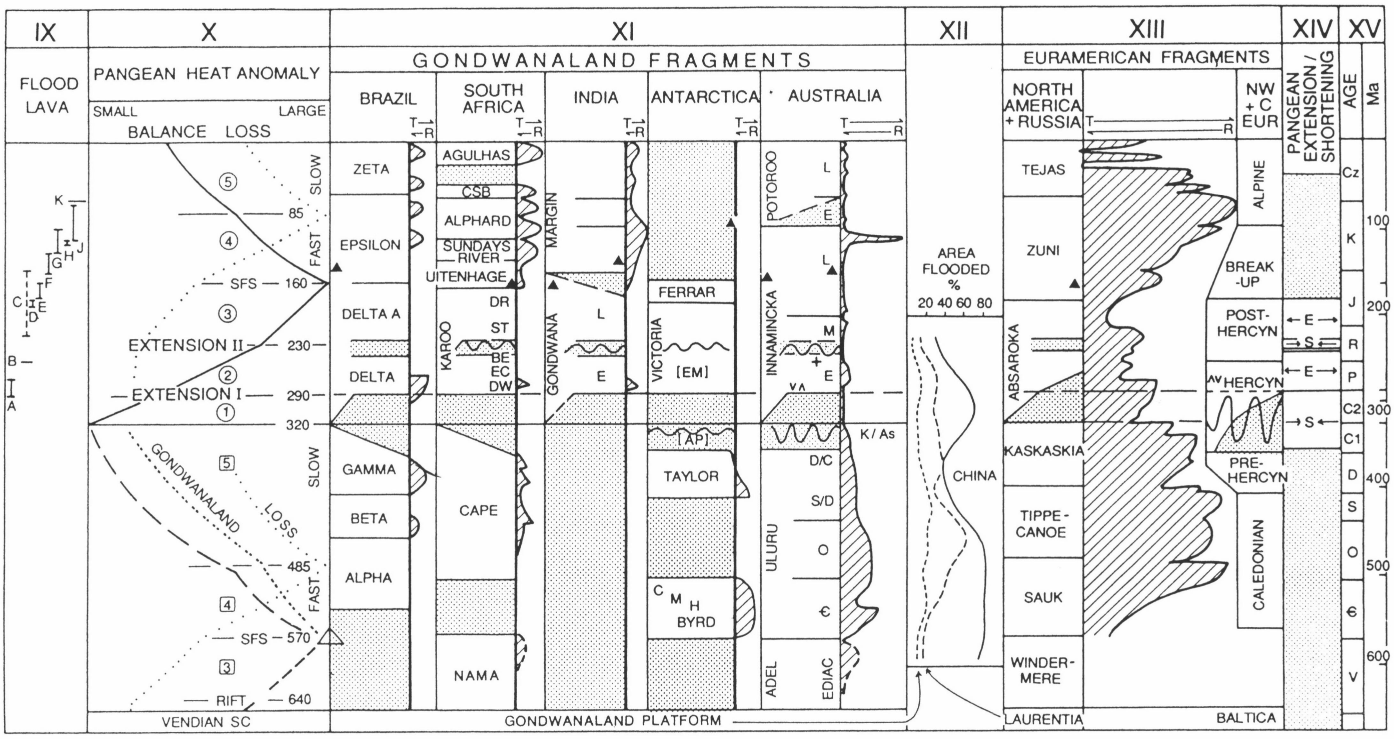
Column X: **320–0 Ma accumulation and dissipation of Pangean heat anomaly in stages 1 through 5 — the dotted line traces the rate of loss of heat that drives plate dynamics, emplaces the volcanics, and initiates basin structure; the solid line represents the residual heat or balance. 650–320 Ma — the broken line traces the accumulation and dissipation of the Vendian supercontinental heat anomaly; the dotted line represents the rate of loss of heat; the double dotted line traces the accumulation of Gondwanaland heat anomaly; the triangle denotes breakup; stages 3 to 5 predicted from Pangean (< 320 Ma) model.**

from the northeastern convergent margin. In the early Palaeozoic (Fig. 4), Australia and New Guinea lay inboard of the continental slivers of Sibumasu and west Burma in the northwest and north China in the north, so that the sea had to cross these margins on its way to the internal Bonaparte, Daly, and Georgina Basins (Fig. 4B), as suggested by the affinity of the faunas in these areas (Metcalfe 1993). A detailed palaeogeography of the regions to the northwest and north, at present contentious, may well show a distribution of land and sea similar to that in the Cretaceous. A remaining difference is the long arm of the Aptian sea in Western Australia (Fig. 3B). This area (western Officer Basin and southwestern Canning Basin), as well as the rest of Western Australia outside the Bonaparte Basin, is represented during the Cambrian by a lacuna (Fig. 5) that almost certainly reflects non-deposition.

The palaeogeography in each cycle (cf. Figs 3 & 4) changed from a marginal transgression behind a newly formed passive margin (A), to a wide transgression of an epeiric sea (B), and finally a regression that exposed almost all the continent (C).

Correlations of Australian stages in Pangean cycles A and B

Correlation of the observed events of cycle A (Jurassic and Cretaceous; Table 2, column 2) with those interpreted for cycle B (Neoproterozoic–Cambrian events; column 3) shows an offset of 400 to 415 m.y. The only exception is the end of the regression (event e), offset an anomalously short 310 m.y. from the Late Cretaceous (90 Ma) to the Early Devonian (400 Ma). Which cycle is anomalous is unknown: it could be



Column XI: **Sequences of the 570–320 Ma Gondwanaland platform and of the < 320 Ma Gondwanaland fragments, and transgressive (T) and regressive (R) curves; lacunas are shown by stipple, the onset of drift by triangles, tectonic shortening by wavy lines, and Early Permian extensional volcanics by 'V's. Brazil (Soares et al. 1978). South Africa (Dingle et al. 1983; Veevers et al. 1994c): BE, Beaufort; CSB, Cape St Blaize; DR, Drakensberg; DW, Dwyka; EC, Ecca; ST, Stormberg. India comprises the Gondwana sequence (Veevers & Tewari 1995), divided by the mid-Triassic lacuna into two parts (E, Early, and L, Late), and the overlying sequence of the eastern margin. Antarctica: H, Heritage; M, Minaret; C, Crashsite (Collinson et al. 1994); the Gondwanide shortening is confined to the Ellsworth Mountains (EM; Grunow et al. 1991) and the mid-Carboniferous shortening to the Antarctic Peninsula (AP; Milne & Millar 1989). Australia (Veevers 1984; Veevers et al. 1994b): the onset of deposition on the Pangean platform is dated at 290 Ma (epi-Carboniferous or Gzelian, east Australian palynological stage 2), and was accompanied by the eruption of thick transtensional volcanics; the cross at the Permian–Triassic boundary signifies the peak eruption of calc-alkaline ignimbrite in eastern Australia; ADEL, Adelaidean; , Cambrian; D/C, Late Devonian/Early Carboniferous; E, Early; EDIAC, Ediacarian; L, Late; M, Middle; O, Ordovician; S/D, Silurian/Middle Devonian; K/As, Kanimblan/Alice Springs deformation.**

Column XII: **Percentage area of continents flooded by the sea (Algeo & Wilkinson 1991); more detailed curves are presented in Figure 1.**

Column XIII: **Sequences of the 570–320 Ma Laurentia and Baltica, of the 320–160 Ma Pangean platform, and of the < 160 Ma Euramerican fragments, and transgressive (T) and regressive (R) curves (Vail et al. 1977); North American sequences are paralleled by those of Russia (Sloss 1976). North America: sequences from Sloss (1988); in the Permian Basin of Texas and New Mexico, the earliest Permian (286 Ma) Wolfcamp Series overlaps the Central Basin Platform (Sloss 1988, p. 265); the base of the Absaroka II subsequence (268 Ma) is marked by greatly accelerated rates of subsidence (Sloss 1988, p. 39). Northwest and central Europe: main phases of plate boundary reorganisation, from Ziegler (1988); in the Permian basins of Europe, subsidence was initiated in the Oslo (volcanic) Graben and renewed in the half-grabens between Norway and Greenland at the same time (290 Ma; Stephanian B or Gzelian) as sagging in the south was accompanied by the eruption of flood lavas and the deposition of the Rotliegende and later successions (Ziegler 1988; Veevers et al. 1994d); HERCYN, Hercynian.**

due to an anomalous second transgressive peak in cycle B at 480 Ma, or to an anomalous Australian continent-wide uplift at 90 Ma cancelling the North American (?eustatic) sea-level peak at 80 Ma (Fig. 1B).

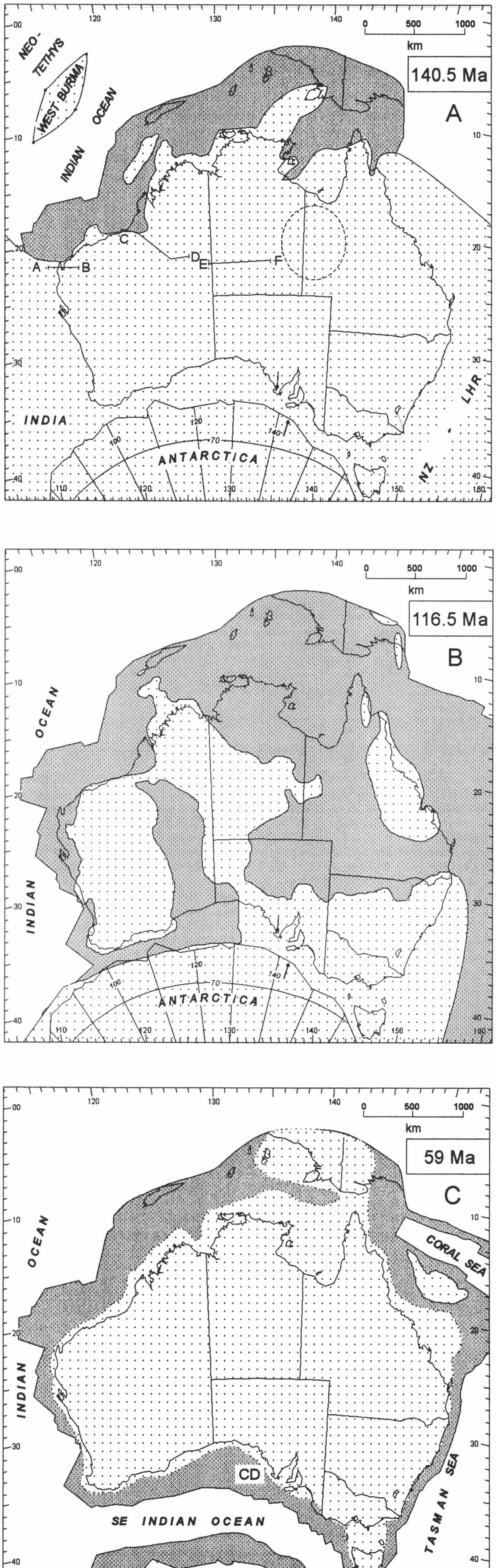
Deviant behaviour of Australia in the Late Cretaceous and Cambrian–Ordovician

Late Cretaceous

The Late Cretaceous major regression in Australia and the minor regression in South America contrast with the peak transgression in North America, seen in plan in Bond (1978, fig. 2), and in the area of platform covered by the sea (Fig. 1 A, B). The sharpest difference is between the Early Cretaceous (Aptian, 116.5 Ma) age of the maximum area of the Australian platform covered by the sea and the Late Cretaceous (Campanian, 80 Ma) age of the widest North American sea, a difference of 36.5 m.y.

Peak plutonic activity in eastern Australia and New Zealand coincided with the Australia-wide Aptian marine transgression (Veevers & Evans 1973, 1975), an example of the Haug effect: 'Times of orogeny are times of transgression of epicontinental seas on the continental interiors'. The flooding of Australia was followed, in the earliest Late Cretaceous or Cenomanian, by an Australia-wide rebound at a time of flooded platforms elsewhere. Russell & Gurnis (1994) explained the Early Cretaceous flooding of eastern Australia by subsidence generated when the dip of the slab decreased. Thereafter, an increase in the dip of the slab, causing uplift, was a consequence of Late Cretaceous back-arc spreading (Mariana-type subduction) replacing Chilean-type subduction off Queensland (Veevers 1991; Fig. 5, 90 Ma). Gallagher et al. (1994) came to a similar conclusion from backstripping and apatite fission-track analysis of eastern Australian basins.

The 3000 km width (between longitudes 152 and 122°E) of the flooded platform and succeeding exposed platform (Fig. 3), however, is not readily attributable to plate boundary effects only. The Early Cretaceous northward tilt of the land surface from the high southern rifted arch reversed to a Late Cretaceous southwesterly tilt from the newly uplifted eastern


140.5 Ma
A
NEO-TETHYS
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km
116.5 Ma
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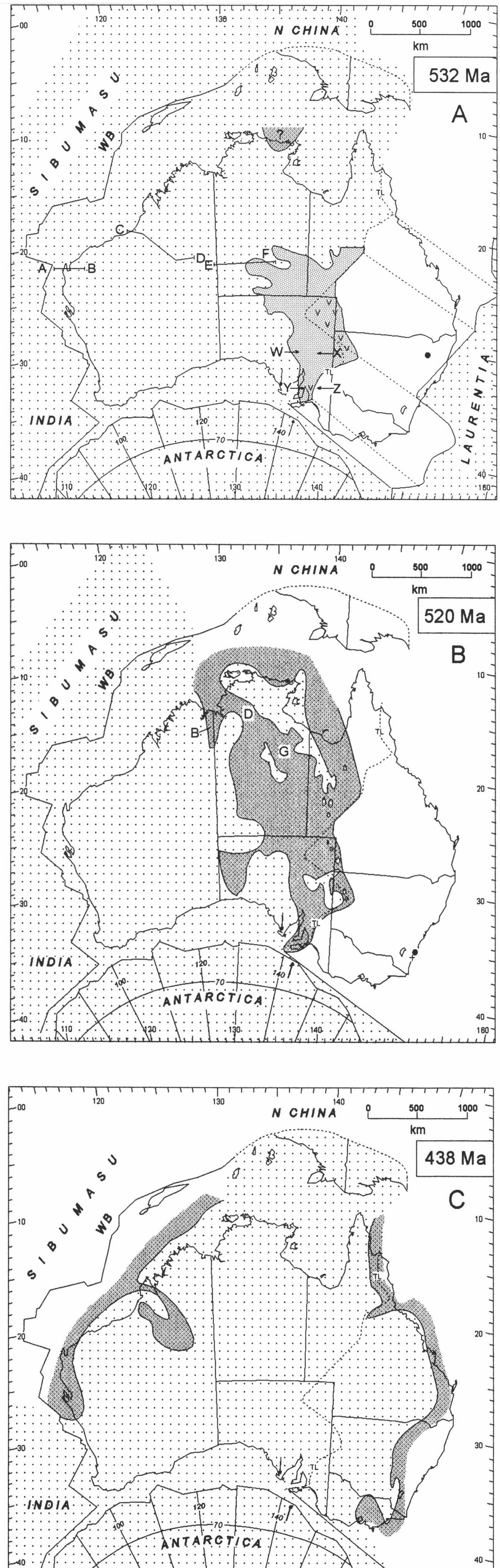
532 Ma
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Table 2. Correlation of events offset 400 Ma.

Event	*Cycle A (320–0 Ma) observed Ma*	*Cycle B (720–320 Ma) interpreted Ma*	*Difference (m.y.)*
a) NW breakup	160	575	415
b) start transgression	140.5	544	403.5
c) W breakup	130		
E breakup		544	414
d) peak transgression	116.5	520	403.5
e) end regression	90	400	310 *
f) change from Chilean to Mariana type subduction	90	490	400

* Offset <<400 m.y.

highlands and southeasterly modestly uplifted (lightly etched) Aptian surface north and west of the head of the Great Australian Bight, so that sediment was funnelled to the Ceduna depocentre (CD in Fig. 3C). Tilting on an east–west axis is not discernible; the dry land of the western half of Australia corresponds to the long-standing exposed shields of the Yilgarn and Pilbara, and the Kimberley and central Northern Territory. The platform therefore subsided and rose, apparently as a unit along a 3000 km east–west axis, across the line of subduction in the east, by a mechanism that extended the Haug effect across the entire platform.

Cambrian–Ordovician

In cycle B, Pangean tectonics possibly led to a similar outcome. Transgressive peaks at 520 and 480 Ma in Australia are offset 70 and 30 m.y. from the 450 Ma peak in North America (Fig. 1A, B). Subduction off southeastern Australia changed from Chilean to Mariana type in the latest Cambrian (490 Ma, **f** in Fig. 5; Powell 1984, p. 290), some 30 m.y. after the first (520 Ma, **d**, Ordian) peak. This compares with the change in subduction at 90 Ma, some 25 m.y. after the 116.5 Ma (Aptian) peak. A difference (cf. Figs 3 and 4) is that the Cambrian transgression barely extended into Western Australia, and may have been due wholly to the eastern active margin.

Conclusions

The buoyant Australian platform was inherited from Neoproterozoic and early Palaeozoic Gondwanaland, whose buoyancy resulted from mafic underplating of the crust during the complex of Pan-African events between 700 and 500 Ma. Even after mid-Jurassic breakup from the southern Gondwanaland province of Pangea, Australia remained buoyed up (in the Great Western Plateau; Veevers 1984, p. 107) by the underplated crust beneath the western two-thirds of the continent west of the Tasman Line.

Figure 3. (left-hand column) Palaeogeography of the Cretaceous transgression and regression of Australia, modified from BMR Palaeogeographic Group (1990), and extended to New Guinea from information in Audley-Charles (1984), Brown et al. (1980), Dow (1977), Harrison (1969), Pigram & Panggabean (1984), and Pigram & Davies (1987), all located in time in the cycle A column of Figure 5. Land denoted by open stipple, shallow sea by fine screen; ocean floor is clear. Adjacent continents and ocean basins from Veevers et al. (1991). Arrows in coastal Antarctica and South Australia indicate the eastern limit of known Archaean rocks (Oliver et al. 1983). NZ-LHR = New Zealand–Lord Howe Rise. A, start of the Early Cretaceous transgression, Berriasian (140.5 Ma), from BMR Palaeogeographic Group (1990) 'Cretaceous 1': the dotted ellipse about the Northern Territory–Queensland border outlines the area of the Georgina–Eromanga basin covered by the sea for a total of 70 m.y. during the Phanerozoic (column A of Fig. 1); AB–CD–EF denotes the location of Figure 5. B, peak transgression, Aptian (116.5 Ma), from BMR Palaeogeographic Group (1990) 'Cretaceous 4', modified to show the sea entering the Styx Basin on the coast of central Queensland, as indicated by Albian microplankton in the Styx Coal Measures (de Jersey 1960, p. 331–332). C, after the Late Cretaceous regression, Paleocene–early Eocene (59 Ma), from BMR Palaeogeographic Group (1990), 'Cainozoic 1'. CD = Ceduna depocentre, at the focus of centripetal drainage (not shown) in the Late Cretaceous.

Figure 4. (right-hand column) Paleogeography a (400 m.y.) cycle earlier, in the Cambrian–Ordovician–Silurian, modified from BMR Palaeogeographic Group (1990) by showing the continental terranes of southeast Asia (North China, SIBUMASU = SInica, BUrma, MAlaya, SUmatra) in their original position (Metcalfe, 1993, fig. 5), but not showing Tasmania, whose precise position during the early Palaeozoic is obscure. Located in the cycle B column of Figure 5. Land denoted by open stipple, shallow sea by fine screen; ocean floor is clear. Adjacent continents and ocean basins from Veevers et al. (1991). Arrows in coastal Antarctica and South Australia indicate the eastern limit of known Archaean rocks (Oliver et al. 1983). The shoreline transgressed from the east, except in C, where a shallow sea advanced additionally from the west; also shown is the shelf-edge break (eastern edge of shading) on the eastern (oceanward) side, marking the approximate position of the eastward-jumping continent–ocean boundary, initially formed along the Tasman Line (TL) during the earliest Cambrian (544 Ma) breakup of Laurentia from Australia–Antarctica (Bond et al. 1985; von der Borch 1980). TL = Tasman Line. A, start of the Cambrian transgression, Early Cambrian (532 Ma), from BMR Palaeogeographic Group (1990) 'Cambrian 1' or Cook's (1988) 'Cambrian 1a', but modified by regarding (i) the Antrim Plateau Volcanics and equivalents in northern Australia as older than Early Cambrian (= Ediacarian), so that the only rocks north of latitude 20°S which are possibly Early Cambrian are those barren strata beneath the Middle Cambrian (Templetonian) rocks of northern Arnhem Land and Elcho Island (Cook 1988, column 1; Bradshaw et al. 1990, p. 114); and (ii), a modification from Cook (1988), the Ordian stage as Middle Cambrian (cf. Shergold 1995), calibrated as 520 Ma. Early Cambrian formations are given in Walter & Veevers (1996, fig. 2), and include the Chandler Formation in the Amadeus Basin, whose extent is taken from Wells et al. (1970, p. 54); the volcanics (v), from Preiss (1987, fig. 104), were erupted probably in a back-arc basin, on the side of the ocean that opened (at an assumed 7 cm y^{-1}) between Australia–Antarctica and Laurentia; the filled circle denotes an ophiolite with 530 ± 6 Ma zircons from upper Bingara, northeastern New South Wales (Aitchison et al. 1992), brought to this location by subsequent subduction; the conjugate margin of Laurentia is sketched (as dry land) on the other side of the juvenile palaeo-Pacific Ocean. AB–CD–EF, WX, and YZ denote the location of Figure 5. B, peak Cambrian transgression, Ordian (520 Ma), from BMR Palaeogeographic Group (1990) 'Cambrian 2', but modified by eliminating the Babbagoola beds of the western Officer Basin (Cook 1988, column 19), now regarded as Ediacarian (Walter & Veevers 1996, fig. 4). The filled circle denotes Middle Cambrian marine fossils in a basaltic breccia of the Wagonga beds south of Batemans Bay, interpreted as part of a seamount incorporated as an exotic terrane within an accretionary prism during Middle to Late Ordovician subduction (Bischoff & Prendergast 1987); the cross denotes similar but barren rocks at Narooma (Miller & Gray 1995); B, Bonaparte; D, Daly; G, Georgina. C, end of the early Palaeozoic transgression, Early Silurian or Llandovery (438 Ma), modified from BMR Palaeogeographic Group (1990) 'Silurian 1' from information about the intertidal Sahara Formation in the Canning Basin (Romine et al. 1994) and the middle Ajana Formation in the Carnarvon Basin (Gorter et al. 1994).

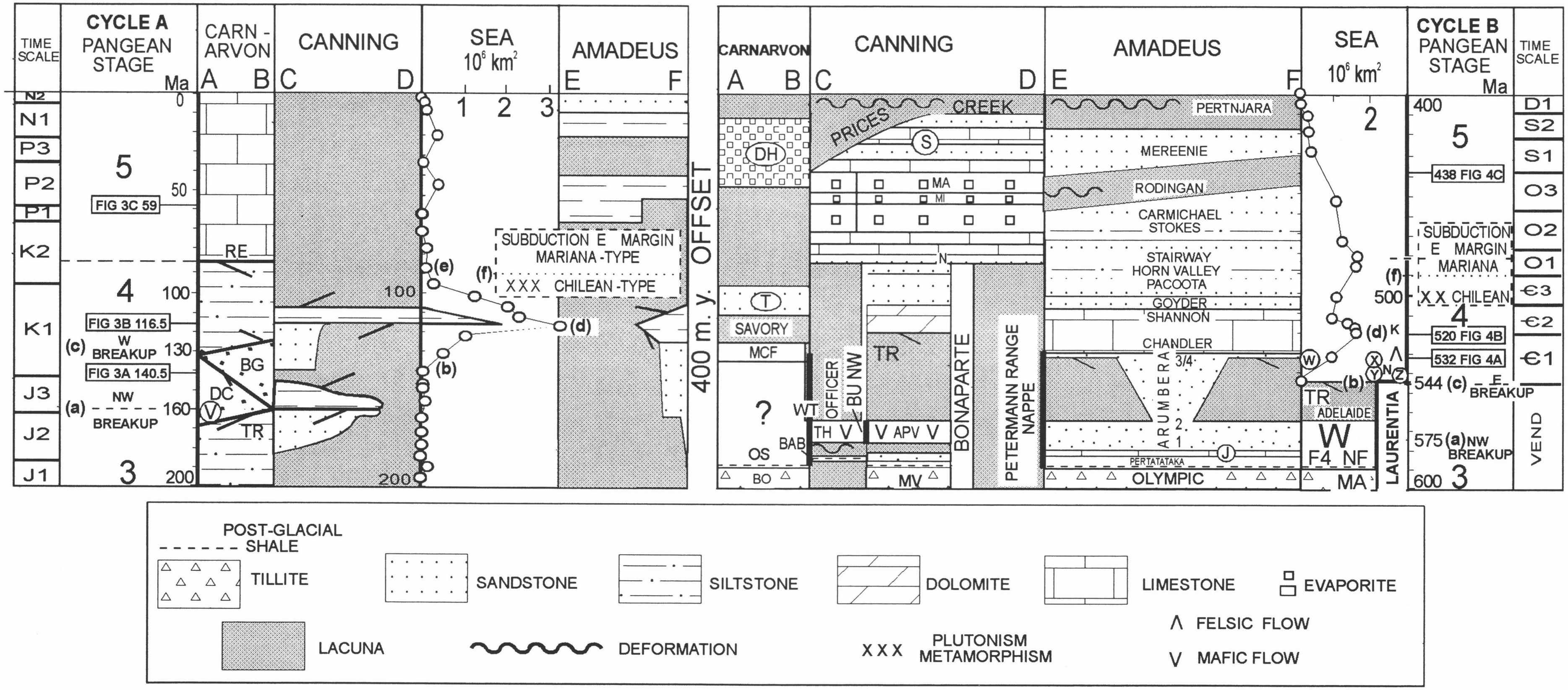

Figure 5. Time–space diagrams from 200 to 0 Ma in Pangean cycle A and, offset 400 m.y., from 600 to 400 Ma in cycle B, along the 1900 km line of AB–CD–EF, and another 100 km along lines WX and YZ (in lower part of 'SEA' column), located in Figures 3A and 4A; modified (and added to) from figure 4 and appendix of Walter & Veevers (1996). Area of platform sea from Figure 1A. In the columns of Pangean cycles and stages (Veevers 1990, 1994), boxed annotations indicate the ages of time-slices represented in Figures 3 and 4, wherein A is at the start and B is at the peak of the transgression and C is at different intervals within the regression. RE = regression; TR = transgression. *Carnarvon Basin (AB), cycle A*: BG = Barrow Group; DC = Dingo Claystone; encircled V at 160 Ma = Wandagee province of picritic diatremes coincident with the age of breakup on the northwest. *Cycle B*: DH = Dirk Hartog Formation; T = Tumblagooda Sandstone; *Savory Basin*: MCF = McFadden Formation; BO = Boondawari Formation diamictite; OS = overlying siltstone. *Canning Basin (CD), cycle A*: shallow transgression at 160 Ma, and peak at 116.5 Ma. *Cycle B*: MA = Mallowa Salt; MI = Minjoo Salt; N = Nambeet Formation; S = Sahara Formation; this sequence succeeds Ordian to earliest Ordovician marine rocks in the *Bonaparte Basin*, which succeed, in turn, the Antrim Plateau Volcanics (APV) and the Moonlight Valley Tillite (MV) and, in the *Officer Basin*, the equivalent Table Hill Volcanics (TH) and Babbagoola beds (BAB); the volcanics are interpreted as indicating breakup to the northwest (BU NW); on the northern and eastern edge of the Officer Basin, the Musgrave Block was uplifted at 590 Ma during movement along the Woodroffe Thrust (WT) in the south and the Petermann Range Nappe, which borders the southwestern part of the Amadeus Basin. *Amadeus Basin (EF), cycle A*: scattered non-marine sediment was deposited intermittently in the Cainozoic on either side of an Oligocene lacuna (Senior et al. 1995); the area was encroached by the sea at the peak of the Aptian (116.5 Ma) transgression (Veevers 1995); in box (bounded by broken line) — change from Chilean to Mariana type subduction in Cenomanian (90 Ma; f). *Cycle B*: J = Julie Formation. *Eastern Australian margin, cycle B:* in box bounded by broken line — change from Chilean to Mariana type subduction at boundary (490 Ma) between Cambrian and Ordovician. *Adelaide, cycle B*: F4 NF at 590 Ma = facies 4 (shale) of the Nuccaleena Formation; K = Kanmantoo Group; MA = Marinoan glacials; N = Normanville Group; inverted 'V' = Truro Volcanics; W = Wilpena Group. *Laurentia* shown juxtaposed against eastern Australia until breakup about 544 Ma.

In equivalent Late Cretaceous and Late Ordovician stages of the 400 m.y. Pangean supercycle, the Australian platform deviated from the global norm by rising faster than eustatic sea level. Plate boundary events — steeper subduction, underplating of a lower plate along a divergent back-arc boundary — explain uplift in the east, which was apparent from the mid-Cretaceous in the Eastern Highlands. The Eastern Highlands were separated by the Central-Eastern Lowlands from the Great Western Plateau (Veevers, 1984, p. 107), which was buoyed up by 700 to 500 Ma underplating.

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