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Phanerozoic tectonic regimes of Australia reflect global events

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Abstract—Phanerozoic Australia was marked by three regimes: Uluru (570–320 Ma), Innamincka (320–97 Ma) and Potoroo (97–0 Ma). Each regime, a complex of uniform plate-tectonic and palaeo-climatic events at a similar or slowly changing latitude, generated a depositional sequence of distinct facies bounded by unconformities at the margins and by stratigraphic gaps in the interior. The Uluru sequence in the interior is dominated by low-latitude shallow-water (including marine carbonate) deposits, the Innamincka sequence by high-latitude non-marine (including glacial) deposits, and the Potoroo sequence by increasingly lower latitude deposits confined almost wholly to the margins. On the east a change from Chilean- to Mariana-type subduction marked the boundary between the Innamincka and Potoroo regimes. The Australian regimes resemble those of the other Gondwanaland fragments, and in particular the Innamincka resembles the Gondwana sequence of peninsular India. The Gondwanaland regimes, in turn, reflect those that pertained in the rest of the globe, as part of two Phanerozoic super-cycles, each *ca* 400 Ma long, the first Palaeozoic–Early Mesozoic, the second Late Mesozoic–Cenozoic. Each reflects a cycle of mantle convection expressed through time variation in plutonism and hence in the concentration of atmospheric CO_2 and in greenhouse–icehouse effects, in continental dispersion–aggregation (Pangaea) and eustatic sea level, and in sediment type, from marine platform sediment during high sea level to non-marine during low sea level.

INTRODUCTION

IN A comprehensive account of the *Phanerozoic Earth History of Australia* (Veevers 1984), we described three depositional sequences of distinct facies bounded by unconformities at the margins and by stratigraphic gaps or lacunas in the interior that were generated during regimes of uniform plate-tectonic and palaeo-climatic events at a similar or slowly changing latitude. The Uluru regime (570–320 Ma) is characterized by convergence at the eastern or Palaeo-Pacific margin, divergence at the western or Palaeo-Tethyan margin, and by shallow-marine (including carbonate and evaporitic) deposition on the interior platform, all at low latitudes. Intense compressive deformation in Eastern and Central Australia during the mid-Carboniferous was followed in the Innamincka regime (320–97 Ma) by a lacuna across the continental platform. Deposition resumed with widespread subsidence in the Permian in a high-latitude glacial climate (without significant carbonate or evaporite), again with convergence on the east and divergence on the west but now with exclusively non-marine sediment on the interior platform. The Potoroo regime encompassed a change from high to lower latitude; the Pacific margin changed from mainly Chilean-type to wholly Mariana-type subduction by the generation of the marginal basins of the southwest Pacific, the pattern of seafloor spreading in the Indian Ocean changed, including the inception of spreading between Australia and Antarctica, and deposition on the platform resumed in the Cenozoic after a long lacuna.

NEW DATA

The scheme of regimes and sequences has been added to by subsequent (including this) work and incorporated in Table 1 and in Figs. 1 and 2. The changes include the following.

(1) Adoption of the DNAG time scale (Palmer 1983) — dates are cited to single millions of years but must be understood to have a halo of error that widens with age.

(2) Comprehensive interpretations of the terranes that broke off the northwestern margin (Veevers 1988a), of terranes that collided with the northern margin (Pigram & Davies 1987), and of terranes that were displaced by transcurrent motion along, or collided with, the eastern Tasman Fold Belt margin (Powell *et al.* 1990).

(3) The recognition that the change from the Innamincka to the Potoroo regime was marked by a change on the Pacific margin from Chilean- to Mariana-type subduction (Veevers in press).

(4) A refined apparent polar-wander path (Li *et al.* 1990).

(5) A Gondwanaland-wide study of the Late Carboniferous lacuna and glaciation (Powell & Veevers 1987, Veevers & Powell 1987), and the pinpointing of the change from warm to cool seas in eastern Australia as Visean–Namurian or 333 Ma by a fall in brachiopod diversity (Roberts 1981).

(6) Recognition of the Gondwana sequence as a facies of the Pangaean sequence (Veevers 1988b).

(7) Appreciation of the considerable continental extension that preceded breakup between Australia and Antarctica (Etheridge *et al.* 1984, Powell *et al.* 1988).

(8) A study of the global extent of the tectonic events in Pangaea at the earliest Permian boundary between sub-stages I and II of the early Innamincka regime and at

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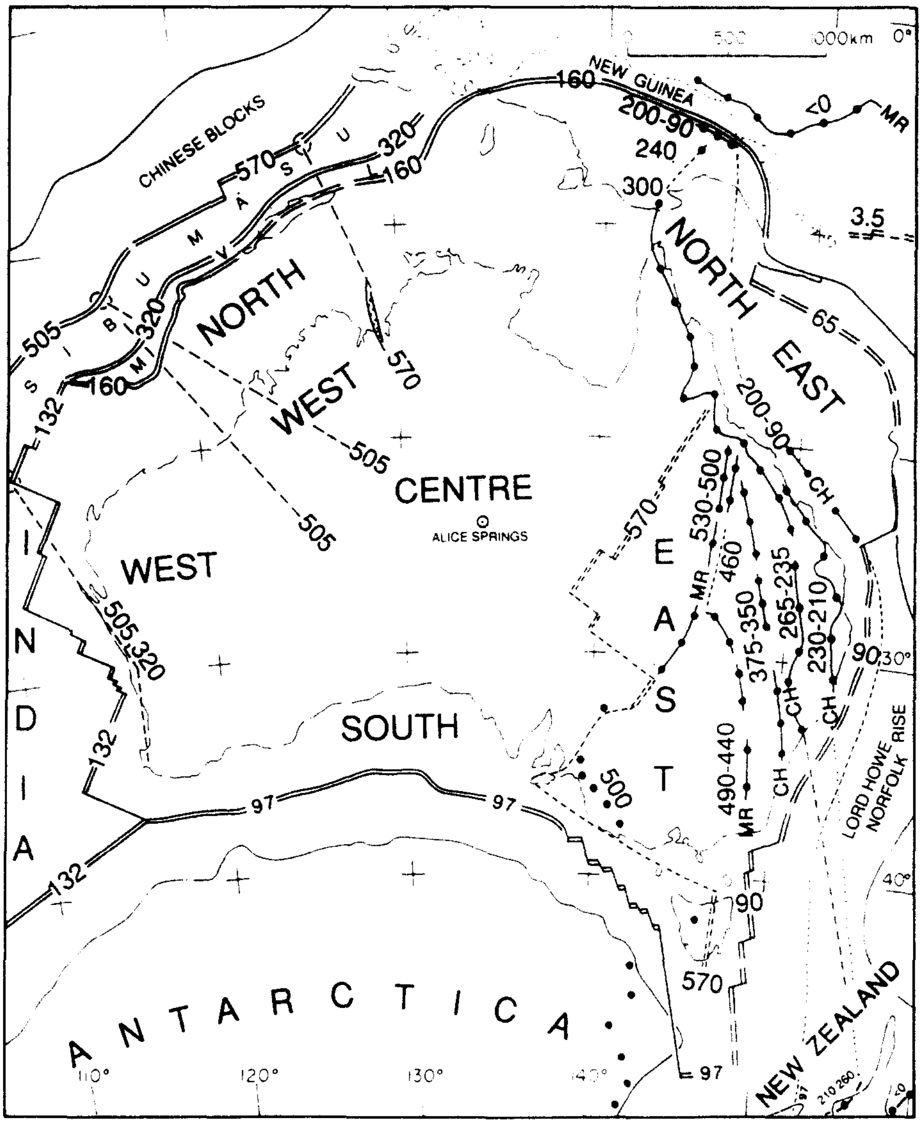


Fig. 1. Synoptic map of Australia within eastern Gondwanaland showing Phanerozoic events located at or near plate boundaries. The map is palinspastic only to the extent that oceanic lithosphere between continental lithosphere has been eliminated; thin continental lithosphere, of greatest extent between the coasts of Australia and Antarctica and east of Australia, has not been restored to its original thickness. The main events shown are the positions of successive divergent plate boundaries and magmatic arcs inboard of convergent plate boundaries. Lines of continental breakup (ages in Ma) from successive generation by seafloor spreading of ocean basins (Palaeo- and Neo-Tethys, Indian Ocean): full double line, and related failed arms: broken line; from successive generation of Pacific marginal seas by back-arc spreading: broken double line. Easternmost limit of successive magmatic arcs of the Tasman Fold Belt: line of filled circles, interpolated by fine broken or dotted line; individual plutons of the Delamerian and Ross (Antarctic) arcs: filled circles; ages (in Ma) refer to the life span or demise of the successive magmatic arcs. Data from Veevers (1984) except northwest (Veevers 1988a), and New Zealand (Bradshaw *et al.* 1981). Coastline for reference only; fine broken line of northern coast of New Guinea indicates extent of allochthonous terranes accreted since 25 Ma (Pigram & Davies 1987). Regions relate to the columns of Fig. 2(a), and ages to the DNAG time scale (Palmer 1983).

the Middle–Late Triassic boundary between the early and middle stages of the Innamincka regime (Veevers 1989).

(9) Recognition here of a boundary between I and II of the Late Innamincka.

(10) Interpolation of magmatic arcs between the east and New Zealand, from information in Bradshaw *et al.* (1981).

PLATE BOUNDARIES AND REGIMES

Figure 1 shows in plan form the successive divergent plate boundaries in the northwest derived from seafloor spreading of the Palaeo- and Neo-Tethyan and Indian Oceans and related failed arms, and on the east the successive magmatic arcs inboard of convergent plate boundaries derived from Chilean (CH)- or Mariana (MR)-type subduction (Uyeda 1981). Note the node or syntaxis of arcs near the coast at 20°S; the modern (<0 Ma) Mariana (MR)-type arc of the southwest Pacific lies wholly east of the previous (>90 Ma) Chilean (CH)-type arcs due to back-arc spreading except at nodes in New Guinea and New Zealand. The broken line of the northern coast of New Guinea indicates the extent of the allochthonous terranes accreted since 25 Ma (Pigram & Davies 1987). The time–space plot of Fig. 2(a) shows additionally the events on the platform, in particular the lacunas that delimit the Innamincka regime. New subdivisions of the regimes are as follows.

(1) Early Innamincka I corresponds to the lacuna that spans the Late Carboniferous (320–286 Ma), and II to the sub-sequence of the Permian (base marked by Eastern Australian Palynological Stage, 2 regarded as Asselian by Archbold 1982) and Early and Middle Triassic (286–230 Ma).

(2) The Late Innamincka regime is divided into two by the inception of seafloor spreading in the northwest and of rifting on the south.

(3) The Potoroo regime is divided into an early stage of Late Cretaceous (97–66 Ma) recovery from the mid-Cretaceous tectonic climax expressed by the platform lacuna, and a late stage of Cenozoic (66–0 Ma) relaxation, expressed by the platform sequence (Veevers in press). A clearer view of the nature of the change from the Innamincka to the Potoroo regime has come from pinpointing the Cenomanian (97–90 Ma) as the switch from Chilean- to Mariana-type subduction, and by recognizing back-arc spreading as the mode of Tasman Sea generation behind the southwest Pacific arc, as originally suggested by Hayes & Ringis (1973). The wider column of the east shows the eastward jumps of the magmatic arc-foreland basin (FB)–epicratonic basin (EB) system, and the corresponding sequential stacking in profile of the Jurassic and Cretaceous epicratonic basin, the Permian foreland basin, the Devono-Carboniferous magmatic arc, and the Ordovician forearc basin.

PALAEOLATITUDE

Figure 2(b) summarizes these events alongside profiles of the palaeolatitude and south azimuth of Alice Springs and of the sequence of the Australian platform. In the Uluru regime, Alice Springs lay within the tropics, in the Early Innamincka within the south polar circle, in the Middle and Late Innamincka and Early Potoroo just north of the south polar circle, and in the Late Potoroo migrated northward to the Tropic of Capricorn. Throughout the Phanerozoic, the azimuth—the bearing of the south pole from Alice Springs—lay within the southern semi-circle between extremes of 106° and 249°; in the Uluru regime, the azimuth lay within the SSW quadrant between 164° and 249° except for an extreme value of 113° at 420 Ma; in the Innamincka regime, within the SE quadrant between 106° and 165°; and in the Potoroo regime, diminishes smoothly from 195° at 66 Ma to today's 180°. In summary, the Uluru regime is characterized by alternating clockwise and counterclockwise rotations of Australia astride the Equator, in episodes 60–90 Ma, long, until the Early Carboniferous when there was a rapid poleward shift of the continent. Australia stayed in polar latitudes for most of the Innamincka regime with little azimuthal rotation, and began a slow counterclockwise rotation as it drifted north during the Potoroo.

GONDWANALAND CORRELATION

The Australian tectonic regimes resemble those of the other Gondwanaland fragments whether expressed by the various generations of the convergent Pacific province, divergent Tethyan–Indian province, or interior or Gondwanan province. The most vivid example is the Gondwana sequence of peninsular India (glacials succeeded by non-marine detritals) and its equivalents in Australia (Innamincka), Antarctica (Victoria), southern Africa (Karoo = Dwyka [DA], Ecca [EA], Beaufort [BT], Stormberg [SG] and Drakensberg [DG] of Fig. 2b), and South America (Santa Catarina = Delta and Delta-A of Fig. 2b) that follow the Late Carboniferous lacuna. Covering one-third of the Earth's circumference, Gondwanaland was crossed by many latitude zones so that at the other end of Gondwanaland from Australia, northern Brazil had an inverse climate: frigid (higher latitude) in much of the Middle Palaeozoic and warm (carbonates and evaporites in lower latitudes) in the Permian. With this allowance for latitude, the regime and sequence are the same throughout Gondwanaland and additionally in North America (Sloss & Speed 1974, Absaroka in Fig. 2b) and the rest of Pangaea (Veevers 1988b) such that the Gondwana sequence is recognized as the southern glacial facies of the Pangaea super-sequence, characterized by non-marine strata.

GLOBAL CORRELATION

Pangaean tectonics

The Pangaea super-sequence correlates, in turn, with the low sea level during the aggregation of the continents in Pangaea in the Late Palaeozoic and Early Mesozoic (Fig. 2b), and represents the end of the first Phanerozoic Wilson cycle, *ca* 400 Ma, long, from the breakup of Proto-Pangaea at the start of the Cambrian (570 Ma, point O in Table 1 and Fig. 2b) to the breakup of Pangaea in the Jurassic (160 Ma, point O′), at the start of the second cycle. Fischer (1984) pointed out the correlation of high sea level with North American granite emplacement and global greenhouse state alternating with icehouse state. Moreover, as elaborated by Worsley *et al.* (1984), he interpreted the correlation as reflecting a cycle of mantle convection expressed in continental dispersal–aggregation (Pangaea) and change of eustatic sea level and in sediment type, from marine platform sediment during high sea level to non-marine during low sea level. In this scheme, the Gondwana sequence is a facies of the Pangaean super-sequence that was generated during slow mantle convection reflected in continental aggregation, and lowered plutonism and sea level, and an icehouse state. Older sequences in the Early–Middle Palaeozoic and younger ones in the Late Mesozoic–Cenozoic were generated during fast mantle convection reflected in rapid continental dispersal, a higher rate of plutonism, higher sea level, and a greenhouse state. In the Late Cenozoic, the attitude of the continents athwart the latitudinal climatic belts and the insulation of a high-standing Antarctica from the rest of the ocean by a circumferential surface current have brought about a presumably brief icehouse episode within a long greenhouse interval.

The regimes can be understood in terms of the heat engine that drives the cycle. Heat accumulates in, and is subsequently dissipated from, the mantle beneath Pangaea (Anderson 1982), giving rise to five stages (Veevers 1989) (Table 1, Fig. 2b), as follows:

(1) Late Carboniferous (320–286 Ma) continuing accumulation of heat without sensible loss, marked in Australia by the platform lacuna of sub-stage I of the Early Innamincka regime;

(2) continued net gain of heat with some surface loss, shown by the earliest Permian (286 Ma) phase of sagging and hotspot lavas, and marked in Australia by the boundary between I and II in the Early Innamincka regime;

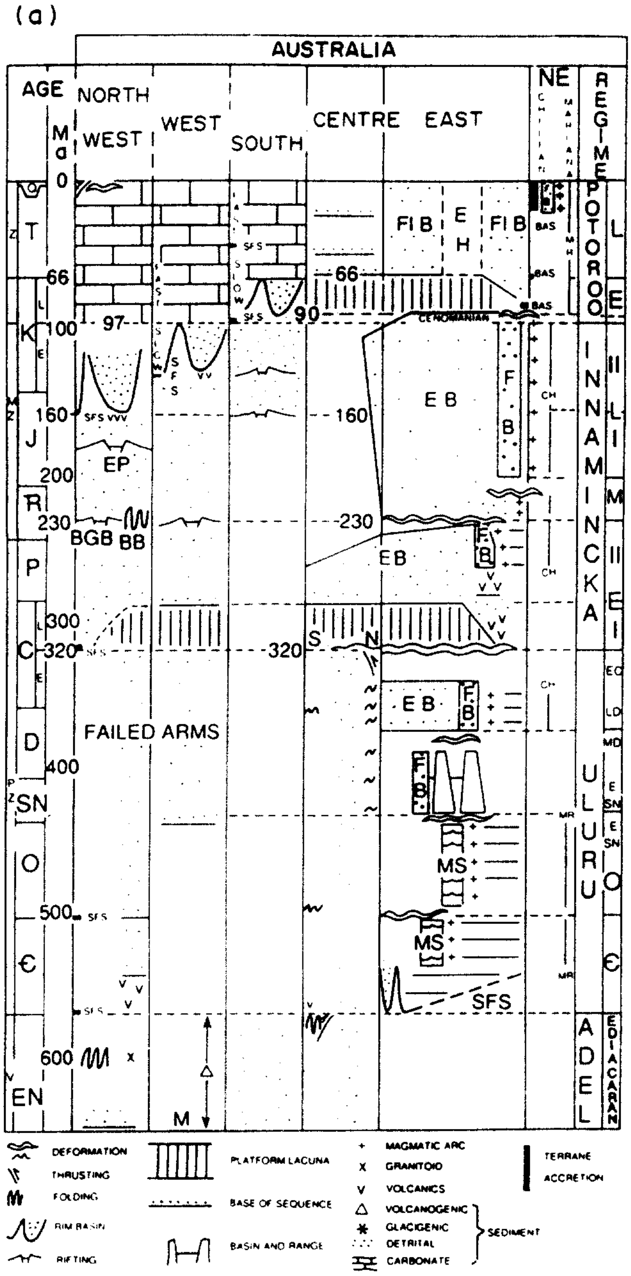
(3) mid-Triassic to mid-Jurassic peak of stored heat marked by the Middle–Late Triassic (230 Ma) rift phase, at the Early–Middle Innamincka boundary;

(4) Middle–Late Jurassic (160 Ma) net loss of heat marked by the onset of fast seafloor spreading in the Atlantic and Indian Oceans, and by the peak eruption of hotspot lavas, at the boundary between sub-stages I and II of the Late Innamincka, at the onset of rifting on the southern margin, seafloor spreading off the northwest, and the start of a marine transgression of the platform;

(5) continued net loss of heat shown by Late Cretaceous (85 Ma) to present slow seafloor spreading, during the Potoroo regime. The breakup of Pangaea 160 Ma ago at the start of the second Wilson cycle of the Phanerozoic, and the preceding rift (230 Ma), sag (286 Ma) and heat accumulation stages (320 Ma) are neotectonic in that the oceanic and margin structures generated by these events remain in place today. Nowhere are the neotectonic structures more diverse and better preserved and documented than in Australia and its surrounding ocean. Each of the Pangaean heat stages described above has a strong reflection in this diverse geological record as a stage of the regimes. We conclude therefore that the chief tectonic events during the Innamincka and Potoroo regimes and their stages reflect the first two orders of the global pattern.

Tectonics during the continental dispersal between Proto-Pangaea and Pangaea

The first 300 Ma of the Phanerozoic are another matter. No Palaeozoic ocean floor is preserved *in situ* so that it can be reconstructed only from evidence available on the continents. The Uluru regime, operating from the breakup (*ca* 570 Ma) of Proto-Pangaea (Bond *et al.* 1984) to the initial coalescence of Pangaea (320 Ma), likewise reflects the first-order global pattern but the second-order pattern is less clear. Differences are as follows (Fig. 2).



(1) The platform sequences of the Uluru regime match neither the correlated ones of Brazil, North America and Russian Platform (Sloss 1976), nor the southern African sequence.

(2) The earliest Middle Cambrian peak transgression of the Australian platform is not represented in the global sea level curve.

(3) The Middle Arenig to end-Llanvirn peak (480 Ma) of the Ordovician transgression (Webby 1978) lags behind the peak global (Brazilian, North American and Russian Platform—Sloss 1976) transgression by some 25 Ma.

(4) The subsequent Late Ordovician to mid-Carboniferous regression of Australia lacks the Early Silurian transgressive peak of the Table Mountain Group of South Africa and the Beta and Tippecanoe sequences of America, and the Middle–Late Devonian

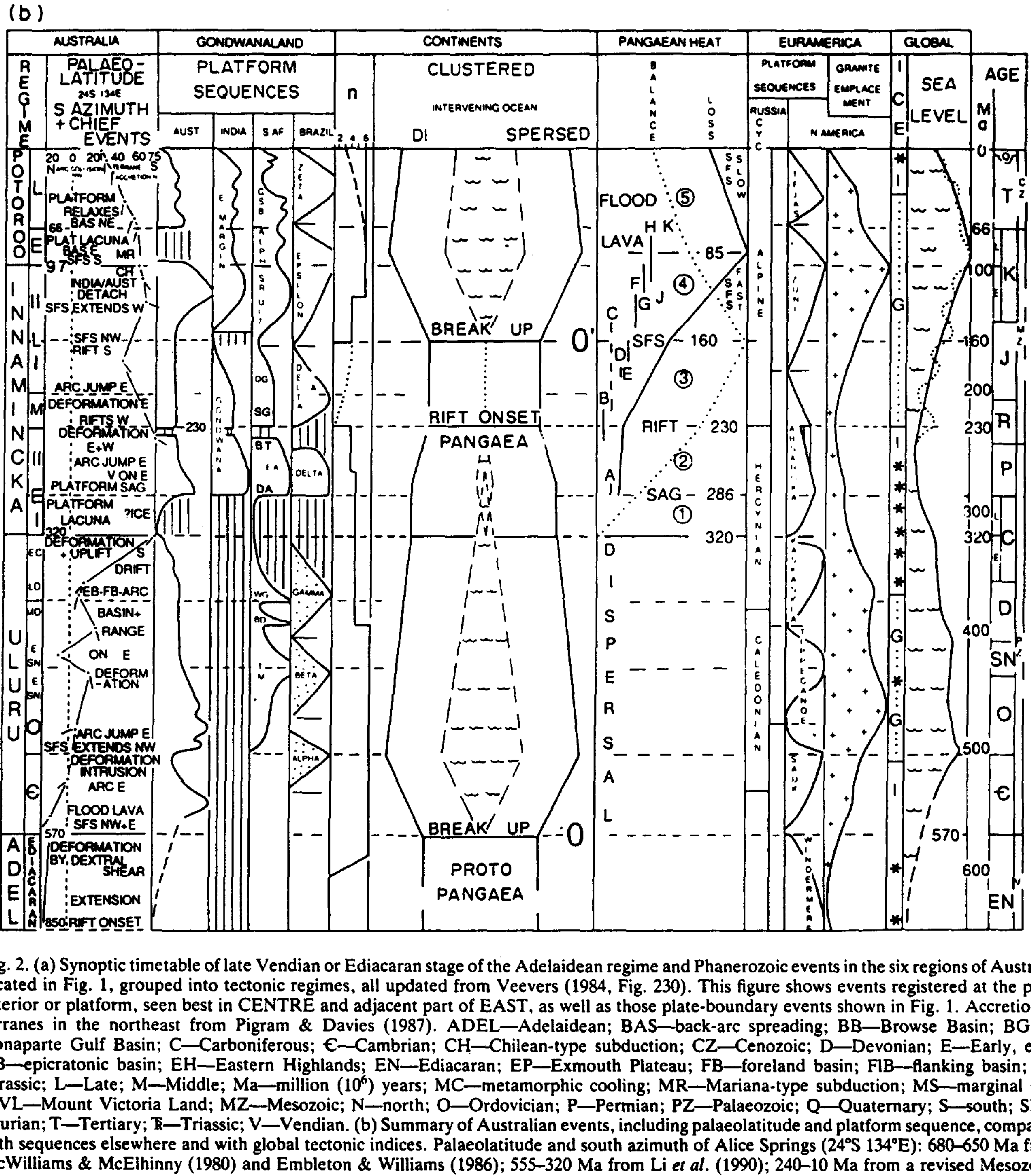


Fig. 2. (a) Synoptic timetable of late Vendian or Ediacaran stage of the Adelaidean regime and Phanerozoic events in the six regions of Australia located in Fig. 1, grouped into tectonic regimes, all updated from Veevers (1984, Fig. 230). This figure shows events registered at the plate interior or platform, seen best in CENTRE and adjacent part of EAST, as well as those plate-boundary events shown in Fig. 1. Accretion of terranes in the northeast from Pigram & Davies (1987). ADEL—Adelaidean; BAS—back-arc spreading; BB—Browse Basin; BGB—Bonaparte Gulf Basin; C—Carboniferous; Є—Cambrian; CH—Chilean-type subduction; CZ—Cenozoic; D—Devonian; E—Early, east; EB—epicratonic basin; EH—Eastern Highlands; EN—Ediacaran; EP—Exmouth Plateau; FB—foreland basin; FlB—flanking basin; J—Jurassic; L—Late; M—Middle; Ma—million (10^6) years; MC—metamorphic cooling; MR—Mariana-type subduction; MS—marginal sea; MVL—Mount Victoria Land; MZ—Mesozoic; N—north; O—Ordovician; P—Permian; PZ—Palaeozoic; Q—Quaternary; S—south; SN—Silurian; T—Tertiary; Ꞧ—Triassic; V—Vendian. (b) Summary of Australian events, including palaeolatitude and platform sequence, compared with sequences elsewhere and with global tectonic indices. Palaeolatitude and south azimuth of Alice Springs (24°S 134°E): 680–650 Ma from McWilliams & McElhinny (1980) and Embleton & Williams (1986); 555–320 Ma from Li *et al.* (1990); 240–10 Ma from a revised Mesozoic-Cenozoic apparent polar-wander path by Li & Powell (unpublished 1988) derived from Embleton (1984), Idnurm (1985, 1986) and from Klootwijk & Peirce (1979) by using rotation poles from Powell *et al.* (1988) to transfer palaeomagnetic poles from India to Australia. Chief events summarized from (a) and Veevers (1984, Fig. 230) range from the earliest part of the timetable, extended to show the onset of Adelaidean rifting (*ca* 850 Ma) (von der Borch 1980), to the modern (<25 Ma) terrane accretion in the north and continent–arc collision in the northwest. Platform sequences (onlap to the right, offlap to the left): Australia from Veevers (1984, Fig. 230) with transgressions in the Ordovician from Webby (1978) and in the Aptian from Frakes *et al.* (1987), and, with India, southern Africa (pre-Permian from Boucot *et al.* 1983), Brazil, Russia and North America, from Veevers (1988b). Rest of information from Veevers (1989). In number (*n*) and clustered-dispersed state of the continents, O and O′ are the comparable breakup stages of ProtoPangaea and Pangaea; the dotted line from 230 to 160 Ma indicates the rift stage of Pangaea and the increasing number of incipient continents. Accumulation and dissipation of the Pangaean heat anomaly in stages 1–5; rate of the loss of heat (full line) that drives plate tectonics, emplaces volcanics, and initiates basin structure, and residual heat or balance (dotted line). Late Palaeozoic and Mesozoic flood lavas: A, European and eastern Australia; B, Siberian Traps; C, Amazon; D, Karoo; E, Transantarctic and Tasmanian; F, Serra Geral; G, Pacific ridge-crest, H, Pacific mid-plate; J, Rajmahal; and K, Deccan. North American granite emplacement, ice (asterisk indicates glacial occurrence within alternating icehouse (I) and greenhouse (G) states), and sea level, all from Fischer (1984), including the first-order sea level curve for the Palaeozoic from Vail *et al.* (1977) and later from Haq *et al.* (1987) smoothed from the long-term curve (dotted line). AUST—Australia; BD—Bokkeveld; BT—Beaufort; CSB—Cape St Blaize; DA—Dwyka; DG—Drakensberg; EA—Ecca; G—greenhouse state; I—icehouse state; SAF—southern Africa; SG—Stormberg; SR—Sundays River; TM—Table Mountain Group; UIT—Uitenhage; WG—Witteberg Group; *—glacial occurrence.

Table 1. Tectonic regimes (and stratigraphical sequences) of Adelaidean and Phanerozoic Australia compared with global cycles. O–O′ delimit the early Phanerozoic Wilson cycle, from breakup to breakup, and O′ to the present the current one. From Veevers (1984, p. 222) with additional data, and calibrated to DNAG time scale (Palmer 1983)

Regime and sequence	Ma	Stage	Ma		Global cycle	
Potoroo	97–0	Late	66–0			
		Early	97–66	85–0	(5) slow SFS	
Innamincka	320–90	Cenomanian	97–90			
		Interregnum				
		II	160–90	160–85	(4) fast SFS	
		Late				O′
		I	205–160	–160	(3) rift	
		Middle	230–205	230		
		II	286–230	286–230	(2) sag	
		Early				
		I	320–286	320–286	(1) initial Pangaea	
Uluru	570–320	Late D/E C	375–320		(c) transgressive peak	
		Early S/M D	430–375		(b) transgressive peak	
		Ord/Early S	505–430		(a) transgressive peak	
		Cambrian	570–505	*ca* 570	(0) dispersal	O
Adelaidean	850–570	Ediacaran	650–570		Proto-Pangaea	

peak of the Witteberg Group of South Africa and the Gamma Sequence of Brazil.

Evidently the transgressive–regressive record of the Uluru regime does not correlate with the global record, but the stage boundaries of the Uluru do. The Cambrian–Ordovician stage boundary, defined by the Delamerian deformation and widespread plutonism, correlates with the peak of the global sea level curve (and the inferred widest dispersal of the continents); the Early Silurian stage boundary, defined in Eastern Australia by the change from Mariana-type subduction to basin-and-range structure, correlates with peak transgressions in South Africa and the Americas; and the Middle–Late Devonian stage boundary, defined by the inception of a Chilean magmatic arc, correlates with the South African and Brazilian peak transgressions. We conclude that though not as clear as those since 320 Ma, the stages of the Uluru regime correlate with global platform events and hence reflect the global pattern.

The 25 Ma lag of the Australian transgression behind the global Ordovician one is echoed by the advance of the Aptian (119–113 Ma) peak transgression of Australia (Frakes *et al.* 1987) some 25 Ma before the global peak in the Turonian (90 Ma) (Haq *et al.* 1987). J. G. Jones & Veevers (Veevers 1984, p. 139) attributed the post-Aptian–Albian regression during the Cenomanian interregnum to the emergence of the magmatic arc from a chain of islands to a volcanic cordillera. Uplift throughout Australia outpaced the rising eustatic sea level to change transgression to regression. This is an example of the active vertical motion of the craton described by Sloss (1988).

DISCUSSION AND CONCLUSION

The three Phanerozoic regimes of Australia are defined by the Late Carboniferous and Late Cretaceous platform lacunas, and the stages of the regimes by the resumption of deposition after the lacunas and by jumps of the system of magmatic arc–foreland or back-arc basin–epicratonic basin and related deformation on the east. All the stage boundaries correspond with global tectonic events related to the Wilson cycle of the growth and decay of oceanic lithosphere and the corresponding breakup and subsequent aggregation of Proto-Pangaea and Pangaea. The complete cycle from the 570 Ma breakup of Proto-Pangaea (O in Table 1 and Fig. 2b) to the 160 Ma breakup of Pangaea (O′) includes the Uluru regime and all but the late stage II of the Innamincka regime; this late stage II and the Potoroo regime represent the existing part of the second cycle. Due to the coupling of the climate with the tectonic cycle through the greenhouse effect of CO_2, the regime sequences have distinct facies, most vividly illustrated by the facies on either side of the Late Carboniferous lacuna: warm-water carbonate below, glacial detrital above. Our classification of the Phanerozoic geological record of Australia originated from local events; we find now that they reinforce the global pattern.

Related events at or near plate boundaries are grossly diachronous. The inception of plate divergence at breakup ranged from 570 to 132 Ma on the west, through 97 Ma on the south and east, to 3.5 Ma east of the Papuan peninsula. During the Phanerozoic, the eastern Australia arc has shifted 5000 km from the Tasman Line to Tonga. Except the Carboniferous and Cretaceous jumps, which coincided with uplift of the entire platform, the jumps had an effect restricted to the east, but all were part of the pattern of global tectonic events that constitute the Wilson cycle.

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