



Biogeographical and geological evidence for a smaller, completely-enclosed Pacific Basin in the Late Cretaceous

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ABSTRACT

Aim To use biogeographical, palaeomagnetic, palaeosedimentary, and plate circuit data from Late Cretaceous regions in and around the Pacific to test the plate tectonic hypothesis of a pre-Pacific superocean.

Location East Asia, Australia, Antarctica, the western Americas, and the Pacific.

Methods Literature surveys of the distributions of Cretaceous, circum-Pacific taxa were compared with palaeomagnetic and palaeosedimentary data. Uncontroversial plate motions based on seafloor spreading data were also used to test the results of the biogeographical and palaeomagnetic analyses.

Results The distributions of Cretaceous terrestrial taxa, mostly dinosaurs, imply direct, continental connections between Australia and East Asia, East Asia and North America, North America and South America, South America and Antarctica, and Antarctica and Australia. Palaeomagnetic, palaeosedimentary, and basic plate circuit analyses require little to no latitudinal motion of the Pacific plate with respect to the surrounding continents. Specifically, the data implies that western North America, East Asia, and the Pacific plate all increased in latitude by roughly the same amount ($c. 11 \pm 5^\circ$) since the Campanian – and that the Pacific Ocean Basin has increased in length north-to-south.

Main conclusions Each of the analyses provides independent corroboration for the same conclusion: the Late Cretaceous Pacific plate was completely enclosed by the surrounding continents and has not experienced significant latitudinal motion with respect to North America, East Asia, or the Bering land bridge. This contrasts significantly with the plate tectonic history of the Pacific, implying instead that the Pacific plate formed *in situ*, pushing the continents apart as the plate and basin expanded. These results also substantiate recent biogeographical analyses that have concluded that a narrower Pacific Ocean Basin in the Mesozoic and early Tertiary provides the most reasonable explanation for the great number of trans-Pacific disjunctions of poor dispersing taxa.

Keywords

Dispersal, expanding Earth theory, Late Cretaceous, Pacific, palaeomagnetism, plate tectonics, vicariance.

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INTRODUCTION

Over the last few decades many biogeographical researchers have contended that hundreds of trans-Pacific disjunctions of poor dispersing taxa are more simply explained by removing the plate tectonic assumption of separation by a now-vanished,

pre-Pacific superocean (Shields, 1979, 1998; Ager, 1986; Matile, 1990; Glasby & Alvarez, 1999; Glasby, 1999; Cranston, 2005; McCarthy, 2003). Each of these analyses has focused on biotic links that extend across the Pacific. Here, additional supporting evidence for a smaller Mesozoic Pacific is presented showing Late Cretaceous biotic and geological links encircling the Pacific,

suggesting terrestrial connections between East Asia and North America, North America and South America, South America and Antarctica, Antarctica and Australia, and Australia and East Asia. Post-Cretaceous plate motions and palaeomagnetic and sedimentary data also support the view of a closed, circum-Pacific, terrestrial circuit, indicating that the northern part of the Pacific plate has experienced little to no latitudinal motion with respect to East Asia, the Bering region and western North America. Each analysis independently corroborates the Expanding Earth theory (EE) view that the Pacific plate formed *in situ*, pushing the continents apart, and the basin was smaller, not significantly larger, in the Mesozoic.

EXPANDING EARTH AND PLATE TECTONICS

Figure 1a depicts the crustal ages of the Earth's seafloor. Since EE does not assume the existence and disappearance of massive ocean plates, the crustal age of the Pacific Ocean Basin rigidly constrains its development (Fig. 1a–d). This view demands that the Pacific plate formed *in situ*, slowly separating the continents.

Figure 1b reunites all the disjunct trans-Pacific fossil taxa from the Late Triassic–Early Jurassic (e.g. Shields, 1998; McCarthy, 2003). Figure 1c shows the complete terrestrial continental enclosure of the Pacific, which, as will be shown, is implied by Late Cretaceous distributions, particularly of dinosaurs. The gap between South America and the west Pacific remained narrow into the Early Tertiary, allowing the interchange of numerous taxa capable of narrow trans-marine dispersal – but not oceanic jumps (for example, the ancestors of New Zealand's frog *Leiopelma* and lizard-like Tuatara, New Caledonia's nearly flightless Kagu, Fiji's Banded Iguana, etc., all of which are most closely related to western American taxa). Also, as will be shown, the *in situ* formation of the Pacific in Fig. 1c matches palaeomagnetic data from the Late Cretaceous–Palaeocene, which demand little to no latitudinal motion of the Pacific plate with respect to East Asia and western North America since that time. Plate tectonics (PT) palaeogeographers, who paint on the *tabula rasa* of vanished ocean plates, still cannot match either the sedimentary, palaeomagnetic or biogeographical data. The removal of the vanished superocean hypothesis solves numerous dilemmas and contradictions that plague PT in a variety of subjects.

In order to maintain a globe of constant radius, PT requires subduction of more than two thirds of the Earth's surface since the Late Triassic, compensating precisely for all seafloor creation. Since the Pacific plate has been locked against the Antarctic plate since *c.* isochron 34 (83.5 Ma), a significant percentage of the missing 200 million km² of the proto-Pacific must have existed north of the Pacific plate (Fig. 2a–c), necessitating, according to PT, a substantial latitudinal gap of now-subducted ocean crust between the Pacific plate's northern boundary and the northern circum-Pacific regions.

These two different versions of Pacific history (Figs 1 & 2) lead to sharply contrasting predictions for palaeomagnetic, palaeosedimentary, and palaeobiogeographical data.

PT'S PACIFIC PALAEOMAGNETIC PROBLEMS

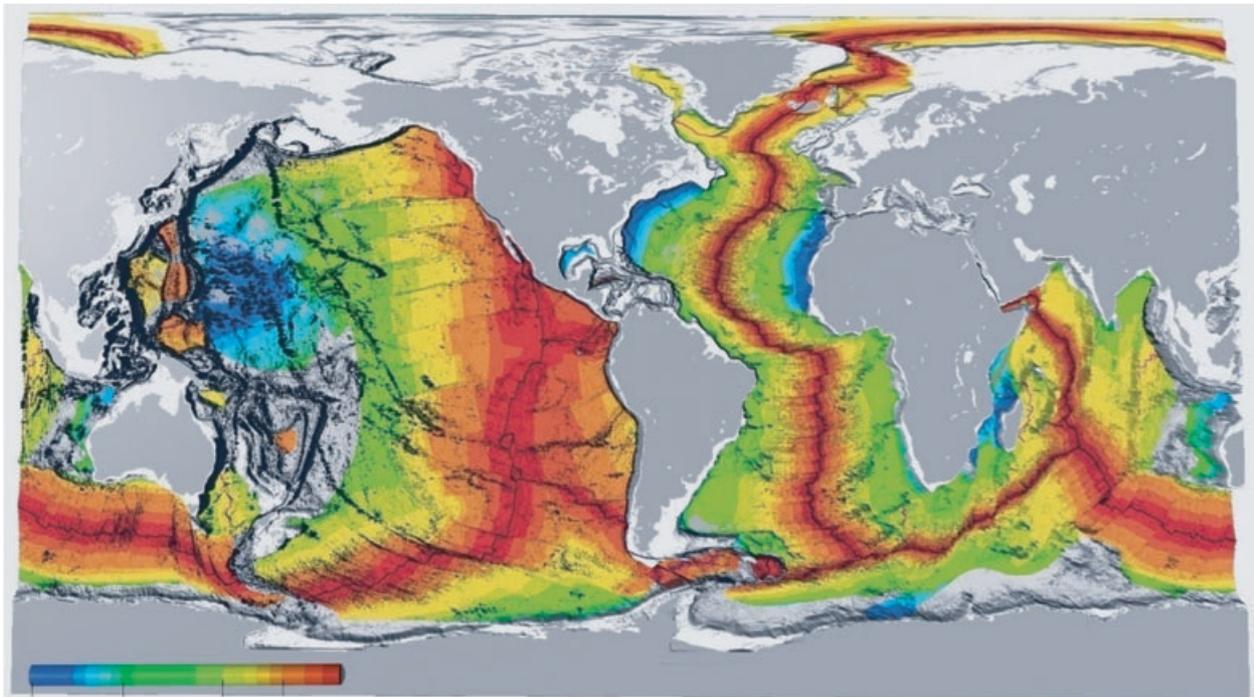
Consistent with the PT history of the Pacific, conventional geological views required that the Detroit Seamount on the northern part of the Pacific plate (Fig. 2a; Scotese, 2001) was over the 'fixed' Hawaiian hotspot (*c.* 19.5° N) during the time of its formation (*c.* 79 Ma). Each segment of the Emperor-Hawaii chain then bubbled and steamed into existence as the plate steadily migrated northward over the hotspot (Wilson, 1963; Morgan, 1971) carrying the Detroit Seamount *c.* 32 latitudinal degrees north to its current latitude (51.3° N). Meanwhile, the circum-Pacific continents drifted 7–15° southward, resulting in *c.* 40–45° (*c.* 4400–5000 km) of northward translation of the Pacific plate relative to the circum-Pacific regions since the Late Cretaceous and essentially the complete subduction of the north proto-Pacific plates. According to PT, the Detroit Seamount has only recently reached its current position (51.3°) adjacent to Kamchatka and the Aleutian trench.

Both the Detroit Seamount near the northern margin of the Pacific plate and all of the north circum-Pacific continental regions have offered a myriad of palaeomagnetic data from the Late Cretaceous and Palaeocene. Of these, perhaps the most telling comparison would involve Kamchatka, the continental peninsula that is currently a few degrees north of the Detroit Seamount on the other side of the Kuril-Kamchatka and Aleutian trench juncture. EE predicts these regions were always in proximity. PT predicts 40–45° of latitudinal separation (4400–5000 km).

According to recent palaeomagnetic analyses, the Detroit Seamount formed in the Late Cretaceous at *c.* 36.3° N (Tarduno *et al.*, 2003) to *c.* 42.8° N (Sager, 2002), roughly 20° north of plate tectonic predictions of the Hawaiian latitude (*c.* 19.5° N), and merely *c.* 8–15° south of its current palaeolatitude (51.3° N). On the continental side of the nearby trench, the Kronotskii peninsula of Kamchatka, currently at 54.5° N, was at 44.8° N (Levashova *et al.*, 2000) in the Late Cretaceous, around 20° south of plate tectonic predictions. This peninsula, which is just 3.5° north of the Detroit Seamount today, was also just a few (2–8.6°) degrees north of the Detroit Seamount in the Late Cretaceous, as EE predicts (Fig. 1c). Contrary to Fig. 2a, 40° of vanished ocean plates did not separate them.

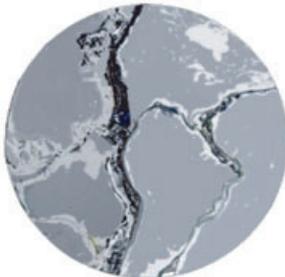
Palaeomagnetic data from other Kamchatka regions also establish this same Late Cretaceous positioning just north of the North Pacific (Pechersky & Shapiro, 1996; Levashova *et al.*, 1997; Kovalenko & Kravchenko-Berezhnoy, 1999; Nokleberg *et al.*, 2000 and references therein). As detailed in Table 1, the vast majority of northern Pacific marginal regions that have provided palaeomagnetic data for the Campanian to the Palaeocene (between *c.* 83 and 55 Ma) have also confirmed little to no northward motion of the Pacific plate with respect to the surrounding continental regions. Specifically, evidence for an increase in latitude of *c.* 6–20° of all circum-Pacific regions since the Late Cretaceous, comparable to the *c.* 8–15° increase of the Detroit Seamount and Pacific plate, includes palaeomagnetic

(a) Ages of Ocean Basin Crust



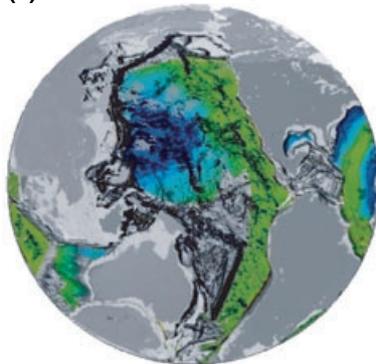
180 120 67 33
Million years before present

(b)



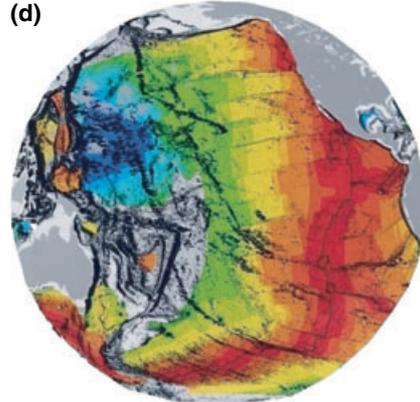
Late Triassic

(c)



Late Cretaceous

(d)

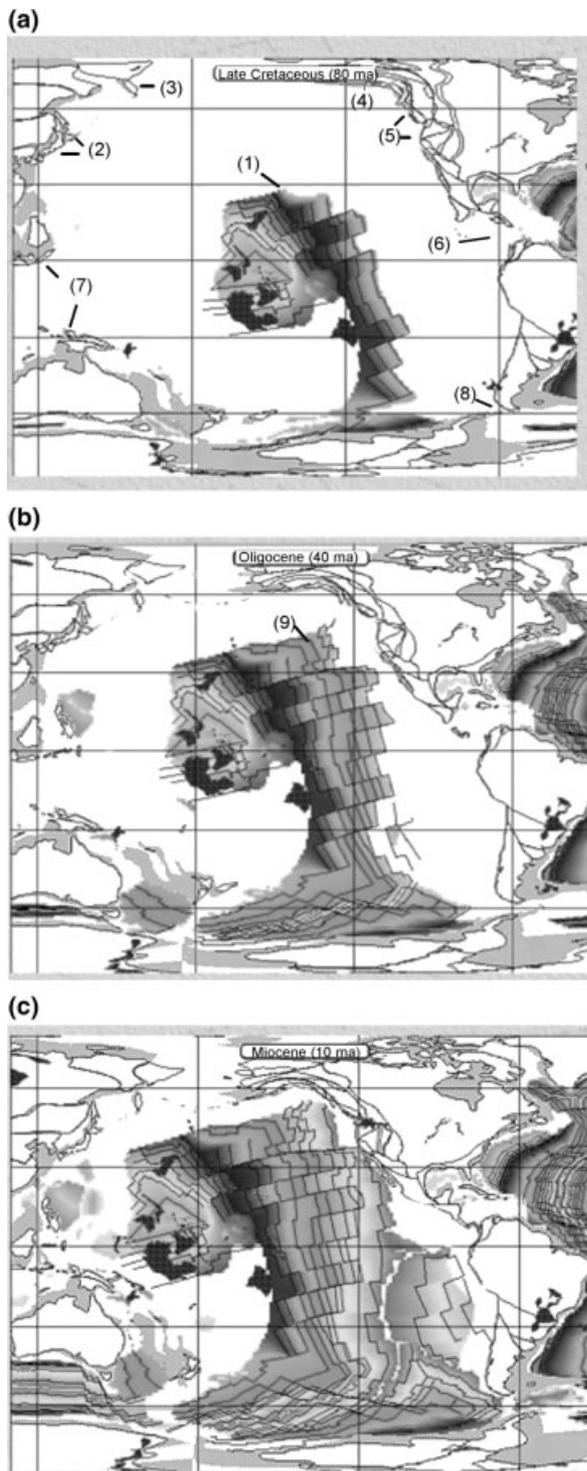


Present

Figure 1 Expanding Earth evolution of the Pacific from the Late Triassic to Late Cretaceous to the present as constrained by crustal age data. Figure 1a is part of an oceanic crustal age poster from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (based on Mueller *et al.*, 1993). All oceanic crust is < 200 Myr old, and most of the South Pacific formed < 40 Ma. Figures 1b–d are EE globes of the Pacific hemisphere. The reconstructions are the result of removing crust that postdate the time period of interest, resulting in convergence of the circum-Pacific continents as the analysis moves backward in time. Eventually, the continents reunite along matching geological outlines in the Early Jurassic/Late Triassic. Some distortion should be expected due to transference of the flat map projections of Fig. 1a to a global view.

analyses from Japan (Itoh, 1988), Hokkaido, Sakhalin and the Kuril Islands (Bazhenov *et al.*, 2001), Kamchatka (Pechersky & Shapiro, 1996; Levashova *et al.*, 1997; Kovalenko & Kravchenko-Berezhnoy, 1999), the Aleutian–Bering bridge and Prince William regions (mostly Palaeocene data, Nokleberg *et al.*, 2000, and references therein), Southern Alaska and northern

British Columbia (Wynne *et al.*, 1995; Stamatakos *et al.*, 2001; Mynatt *et al.*, 2003), Vancouver Island (Ward *et al.*, 1997), Washington (Ague & Brandon, 1996), California (Frei *et al.*, 1984; Kanter & Debiche, 1985; Whidden *et al.*, 1998), Baja Peninsula (Hagstrum & Filmer, 1990; Hagstrum & Sedlock, 1998) and the Caribbean (Acton *et al.*, 2000).



While predicted by EE, the data dramatically depart from PT predictions for the location of both the entire North Pacific as well as every continental region around the North Pacific. Moreover, the data contradict the static global-palaeoradius requirement of $> 40^\circ$ of northward translation of the Pacific plate with respect to Asia and North America. The resulting explanations for this discrepancy have

Figure 2 Plate tectonic evolution of the Pacific from the Late Cretaceous to the Miocene. The figures above (from Scotese, 2001) depict 40° – 45° (*c.* 4400–5000 km) of northward motion of the Pacific plate relative to Eurasia and North America since the Late Cretaceous as massive pre-Pacific plates (white areas surrounding the Pacific plate) are swallowed. Numbers have been added to Scotese's maps (Fig. 2a–c) in order to highlight the following problems: (1) in Fig. 2a points to the location of the Detroit Seamount on the northern section of the Pacific plate. Paleomagnetic data indicate it was actually located at *c.* 36.3° N (Tarduno *et al.*, 2003) to *c.* 42.8° N (Sager, 2002), not south of the 30th parallel. (2) Southwest Japan (Itoh, 1988), Hokkaido, Sakhalin and the lesser Kuril Islands (Bazhenov *et al.*, 2001), depicted here as being significantly north of the Pacific plate were actually south of the Detroit Seamount by *c.* 3 – 12° . (3) Kamchatka, shown as roughly 45° north of the Detroit Seamount, was actually just a few degrees north of the Detroit Seamount, just like today (Levashova *et al.*, 2000). (4) The Aleutian regions on the other side of the Aleutian trench approximately occupied the same relative latitude as the Detroit Seamount (mostly Palaeocene data, Nokleberg *et al.*, 2000, and references therein). (5) Vancouver Island (Ward *et al.*, 1997) and California (Frei *et al.*, 1984; Kanter & Debiche, 1985; Whidden *et al.*, 1998) were south, not north, of the Detroit Seamount. (6) The southern part of the Caribbean occupied an equatorial position (Acton *et al.*, 2000). (6, 7) As will be shown, the large gaps between Australia and East Asia and between North and South America are not biogeographically feasible as the regions share an inordinate number of closely-related terrestrial taxa, including dinosaurs. (8) There could not have been any sort of gap between South America and the Antarctic Peninsula. (9 – Fig. 2b) indicates the location of the continental sediments of the Zodiac Fan, which implies proximity of this section of the Pacific plate with Alaska (Atwater, 1989), its terrestrial source.

generated controversy and debate. One group of PT theories require that practically every region along the northern Pacific margins that has provided palaeomagnetic data for the Late Cretaceous and Palaeocene was displaced significantly southward relative to its respective continent. This is troublesome for the western Pacific because not only do the Asian margins have shallower than expected inclinations in the Late Cretaceous–Palaeocene, so does the rest of Asia (e.g. Ali *et al.*, 2003). This problem is referred to as the 'stable Asia shallow inclination problem' (Ali & Aitchison, 2004). Moreover, the hypothesis of tremendous latitudinal transport (1500–4000 km) of the eastern Pacific marginal terranes with respect to North America, informally known as the 'Baja-British Columbia' hypothesis (e.g. Ward *et al.*, 1997), contradicts a wealth of geological data. For example, in a chemical and isotopic analysis of a Late Cretaceous conglomerate clast assemblage in western California, Schott *et al.* (2004) verify that its source was the nearby southern Sierra Nevada, which 'provides strong evidence that the terranes of western California that lie west of the San Andreas transform system are not exotic or far traveled'. Johnston (2001) has also highlighted this conflict in PT when palaeomagnetic data are compared with various geological facts:

Table 1 Palaeomagnetic data of circum-Pacific regions from East Asia and North America. All site latitudes are in degrees (north), and all motions are given in latitudinal degrees. The number in parentheses that precedes each site refers to numerical indicators in Fig. 2. The last column indicates relative motion of the Pacific plate with respect to these regions. Palaeolatitudinal analyses place the Detroit Seamount somewhere between 36.3° N (± 4.9) (Tarduno *et al.*, 2003) and 42.8° N (+13.2/−7.6) (Sager, 2002) at c. 76–79 Ma. A palaeolatitude of c. 39.3° N for the Detroit Seamount is used for this analysis, entailing an absolute increase in latitude of c. 12° for the Pacific plate since the Late Cretaceous. Relative northward motion of the Pacific plate with respect to the Laurasian region (last column) was determined by subtracting the northward translation of the Laurasian region from 12°. Negative numbers indicate the Pacific plate has actually shifted slightly south with respect to these regions (i.e. the continental region has moved more than 12° north since the Late Cretaceous). EE predicts little to no northward motion of the Pacific plate with respect to the surrounding continental regions (Fig. 1) while PT predicts c. 40–45° (c. 4440–4995 km) of relative northward motion of the Pacific plate (Fig. 2). As the last column indicates, the palaeomagnetic data have confirmed little to no relative motion of the Pacific plate with respect to the surrounding continents

Site, age, reference	Current latitude (°)	Palaeolatitude (°) (error)	Palaeolatitude prediction (PT) (°)	Absolute motion of terrane (° lat.)	Relative motion of Pacific plate (° lat.)
<i>East Asia</i>					
(2) Nohi, Southwest Japan Late Cretaceous (Itoh, 1988)	36	30.6 (+5.8/−5.1)	NA	5.4	6.6
(2) Sakhalin (Chayka) c. 83–65 Ma (Bazhenov <i>et al.</i> , 2001)	46.8	26.6 (± 5.2)	53.9	20.2	−8.2
(2) Hokaido (Yosenkyo) c. 83–65 Ma (Bazhenov <i>et al.</i> , 2001)	43.2	25.0 (± 11)	51.1	18.2	−6.2
(2) Lesser Kuril (Shikotan) c. 70 Ma (Bazhenov <i>et al.</i> , 2001)	43.5	36.5 (± 4)	51.5	7	5
(2) Lesser Kuril (Nemuro) c. 88–84 Ma (Bazhenov <i>et al.</i> , 2001)	43.0	34.5 (± 5.9)	49.7	8.5	3.5
<i>North of the Aleutian Trench</i>					
(3) Kamchatka (Kronotskii Peninsula) c. 83–65 Ma (Levashova <i>et al.</i> , 2000)	54.5	44.8 (± 8)	67.8	9.7	2.3
(3) Kamchatka (Eastern Ranges) c. 83–79 Ma (Levashova <i>et al.</i> , 1997)	56	49.7 (± 5.6)	70	6.3	5.7
(3) Northern Kamchatka (Karaginsky Island) 73–55 Ma (Kovalenko & Kravchenko-Berezhnoy, 1999)	59	c. 45 (± 5)	60–70	14	−2
(4) Southern Alaska 65–55 Ma (Nokleberg <i>et al.</i> , 2000)	56.9 (153.9 W)	47 (+11.6/−9.4)	NA	9.9	2.1
(4) Southern Alaska 65–55 Ma (Nokleberg <i>et al.</i> , 2000)	57.3 (152.3 W)	33.6 (+9.6/−7.8)	NA	23.7	−11.7
(4) Southern Alaska (MacColl Ridge) 80 Ma (Stamatatos <i>et al.</i> , 2001)	62.1 (142.3 W)	53.4 (± 8)	68	8.7	3.3
<i>Western North America</i>					
(5) Southern Canadian Cordillera, British Columbia (Methow Terrane) 85 Ma (Nokleberg <i>et al.</i> , 2000)	51.3	37.4 (± 6)	NA	13.9	−1.9
(5) Vancouver Island (Texada Island) 83–78 Ma (Ward <i>et al.</i> , 1997)	49.5	34.7 (± 5.7)	62	14.8	−2.8
(5) Vancouver Island (Hornby Island) 75–70 Ma (Ward <i>et al.</i> , 1997)	49.5	31.7 (± 3.5)	62	17.8	−5.8
(5) Washington (Mt. Stuart Batholith) 96–93 Ma (Ague & Brandon, 1996)	47.5	30.3 (± 4)	57	17.2	−5.2
(5) Orange County, California (Silverado Formation) 65–55 Ma (Hagstrum & Sedlock, 1998)	33.5	26.7 (± 6)	39	6.8	5.2
(5) San Diego (Point Loma) Late Cretaceous (Hagstrum & Sedlock, 1998)	32.8	21.6 (± 5)	44	11.2	−0.8
(6) Caribbean (Site 882 on North American Plate, east of Yucatan) 49–52 Ma (Acton <i>et al.</i> , 2000)	19.5	7.9 (+5.1/−7.9)	NA	11.6	0.4

Regional and detailed mapping [of western North America] has, however, yet to reveal the strike–slip faults along which such displacements are inferred to have occurred. Correlation of stratigraphy and structures across those strike–slip faults that have been mapped suggests that they have insufficient offset to account for the palaeomagnetic data (references therein). Either the palaeomagnetic data are being interpreted incorrectly, or structures accommodating thousands of kilometres of margin-parallel displacement are being systematically overlooked.

A few have challenged the palaeomagnetic conclusions for some of the western North American regions by contending that tilting could result in a misleading appearance of shallow inclinations and southerly placements. The convolutions of the ensuing debate over tilting and the amount of northward motion of these Western American regions (e.g. Butler *et al.*, 1989, 2001; Ague & Brandon, 1996, 1997; Anderson, 1997; Böhnel *et al.*, 2002) are not particularly relevant to this problem, for, typically, even those researchers who have challenged the original palaeomagnetic conclusions (e.g. Butler *et al.*, 2001; Stamatakos *et al.*, 2001) do still agree that these North American regions were south of their current locations in the Late Cretaceous. For example, although Butler *et al.* (2001) describe the possibility of tilting and '[push] the confidence limits on palaeomagnetic observations toward lower displacement estimates', they agree that their analysis 'still requires 1000 km [c. 9°] post–mid-Cretaceous northward motion for large segments of the North American Cordillera'.

Still other palaeomagnetic evidence can be used to support this same fact. As will be shown below, North America could not have been separated from the Caribbean during the Late Cretaceous as the Caribbean is required to provide the trans-American land bridge for dinosaur interchange. Since the Caribbean was c. 10° south of its current location in the Late Cretaceous (Acton *et al.*, 2000), this implies a similar placement for North America. Moreover, one of the sites studied by Acton *et al.* (2000) is not really part of the Caribbean but sits upon the North American plate, north of the Cayman Trough. Its current latitude is 19.5° N, and its mean palaeolatitude at 52 Ma was 7.9° N, which is 11.6° south of its current location. As expected, the Caribbean plate and this North American site 'has moved northward at roughly the same velocity', which is also the same velocity as the Pacific plate.

Recently, Koppers & Staudigel (2005) showed that $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the bends in Gilbert Ridge and Tokelau Seamounts were much earlier than the bend in the Hawaiian–Emperor chain, contradicting the theory of fixed-hotspots. Koppers & Staudigel concluded that 'absolute Pacific plate motion, for the time period between 80 and 47 Ma is extremely poorly constrained'.

Since mainstream geologists agree that the Atlantic and Indian oceans were closed in the Mesozoic, the Pacific is the only region where predictions between EE and PT substantially differ. Moreover the palaeomagnetic data from in and around the North Pacific have confirmed the expectations of EE and

contradicted those of PT. Perhaps Nokleberg *et al.* (2000) provided the most concise description of this PT dilemma when they wrote that it necessitated either a 'radical reinterpretation of the palaeomagnetic studies' or a 'radical reinterpretation of the geologic data'. In the view of EE, the situation is much simpler. The explanation for why, in the Late Cretaceous/Palaeocene, all the palaeomagnetic data show that the margins of East Asia and North America occupy the same relative latitudes as the Pacific plate is because that is where the continents were. Once that is accepted, the remaining discrepancies in palaeolatitude are significantly less dramatic and likely the result of verifiable motions along strike–slip faults, crustal shortening or extension, motion of the pole, small amounts of continental over-thrusting of the Pacific, compression of latitudinal degrees on a smaller Earth, compaction, tilting, etc.

SEDIMENTARY DATA

Along with the palaeomagnetic facts, sedimentary data also confirm the lack of separation between the northern part of the Pacific plate and the Bering regions/circum-Pacific continents. As has been highlighted by various followers of EE (e.g. Carey, 1988, pp. 184–186), the current location of the Zodiac fan is particularly problematic to PT reconstructions. Ocean fans form from terrestrial sediments deposited by rivers as they empty into the sea. At 40 Ma, the time of the older Zodiac sediments, plate tectonic theory not only places this fan far to the west of the Alaskan drainage region but must set it south of the now vanished Kula plate, in the middle of the ocean, considerably distant from any terrestrial source (Fig. 2b). This problem has also caught the attention of plate tectonic theorists. Tanya Atwater, the researcher who has provided so many invaluable details on the isochronal evolution of the Pacific and helped formulate the current plate tectonic model of the Cenozoic relationship of the Pacific and western North America, described the Zodiac Fan as follows:

This exceedingly voluminous turbidite body covers the great magnetic bight region [in the north central Pacific]. It is continental in origin, is Eocene to Oligocene in age (deposited between c. 40 and 26 Ma), and was fed by channels from the north or northeast [references therein]. Most plate reconstructions place this fan in the center of the ocean at the time it was deposited, thousands of kilometres from land and separated from the land by mid-ocean ridges and trenches.... The reconstructed position of the Zodiac Fan, so far removed from obvious sources, leads one to doubt our standard plate visualizations for the North Pacific. (Atwater, 1989)

This sedimentary evidence is in agreement with the palaeomagnetic data that suggest that in the Late Cretaceous/Palaeocene, Eurasia and North America surrounded the northern half of the Pacific plate just as they do today.

BIOGEOGRAPHICAL DATA AND BASIC EUCLIDEAN GEOGRAPHY

Simple facts of biogeography, plate sizes and Late Mesozoic and Cenozoic motions of the Americas also independently imply the northward motion of North America and an increase in the size of the Pacific Basin since the Cretaceous. In PT, the Cretaceous terrestrial connection among the southern continents, South America, Antarctica, and Australia – as well as among the Laurasian continents, North America and East Asia – is not denied. East Asia and western North America share so many different types of vertebrates in the Late Cretaceous (e.g. Cox, 2000; Lucas & Heckert, 2000) that many researchers refer to it as part of a continuous biotic province called 'Asiamerica' (e.g. Le Loueff, 1991; Cox, 2000; Sanmartin *et al.*, 2001). Tyrannosaurs, hadrosaurs, and ankylosaurs are just a few of the dinosaurs that spread between the regions across the Bering span. This northern terrestrial passage had to exist by the mid-Cretaceous at least as basal hadrosaurids appear in China in the Early Cretaceous (You *et al.*, 2003) and in North America by 95 Ma (Head, 1998). In the south, the biogeographical evidence for a connection among South America, Antarctica, and Australia is well known and, in fact, an Antarctic bridge is the only explanation available to PT theory for the numerous terrestrial biotic links between South America and Australia (e.g. Cox, 2000; Sanmartin & Ronquist, 2004). Even in PT, this connection lasted well into the Cenozoic. As most geologists and biogeographers agree, the southern and northern halves of the circum-Pacific continental circuit were closed.

Also, during the Late Cretaceous many kinds of taxa, particularly dinosaurs, crossed the Western Tethys (or Caribbean) between North and South America (Gayet *et al.*, 1992). This American exchange included hadrosaurs, mammals, lizards, snakes and plants (Pascual *et al.*, 2000; Morley, 2003). Caimans entered South America via the north near the Cretaceous-Tertiary boundary (Brochu, 1999). The late Campanian North American appearance of *Alamosaurus*, a behemoth most closely related to sauropods from Brazil and Argentina (Lehman & Coulson, 2002), demands the re-entry of sauropods into North America from the south prior to this

time (Lucas & Hunt, 1989; Sullivan & Lucas, 2000). All of this requires a direct American land connection and challenges the possibility of significant southward motion of North America with respect to South America since the Late Cretaceous. In fact, despite Fig. 2, localized PT palaeomaps of the Cretaceous Caribbean (Meschede & Frisch, 1998; Pindell *et al.*, 2000) as well as PT papers on the Cretaceous biogeography of the Americas (Morley, 2003) show South America directly connected with North America as far north as the Yucatan peninsula. And if we may discount the rafting or island hopping of hadrosaurs, sauropods, etc., this proximal positioning cannot be avoided.

Given that Antarctica and the Alaskan-Bering land bridge serve as the southern and northern boundaries of the Pacific Basin, respectively, and that the Alaskan-Bering land bridge is actually part of the North American plate (e.g. Gaina *et al.*, 2002) and extends deep into Russia, these Cretaceous connections present a simple problem (Fig. 3): (i) If South America has had to separate from the main body of Antarctica by a minimum of 7 latitudinal degrees and most likely between 12° and 20° since the Cretaceous; (ii) and if over the same period of time, North America and its Bering bridge has had to drift slightly away from South America – and certainly could not have moved significantly closer; (iii) then North America has had to move north with respect to Antarctica since the Cretaceous, and the distance between Antarctica and the Alaskan-Bering bridge must be greater today than at that time. This entails that the Pacific Ocean Basin has increased in length north to south since that time – and the PT requirement of extreme north-south shortening of the basin may be excluded.

Another elementary analysis also implies the same relationship. The current latitudinal extent of the existent Late Cretaceous Pacific plate (80 Ma), from its southern edge at the Campbell plateau of New Zealand (55° S) to its northern point at the Kamchatka-Aleutian trench juncture (55° N) is 110° (c. 12,210 km). Likewise, the latitudinal distance from Tierra del Fuego at the southern tip of South America (55° S) to Kodiak Island, north of the Aleutian trench on the Alaskan-Bering land bridge (56° N), is roughly the same north-south distance: 111° (c. 12,321 km). Since the southern edges of both South America and the Pacific plate were adjacent

North-south expansion of Pacific Basin

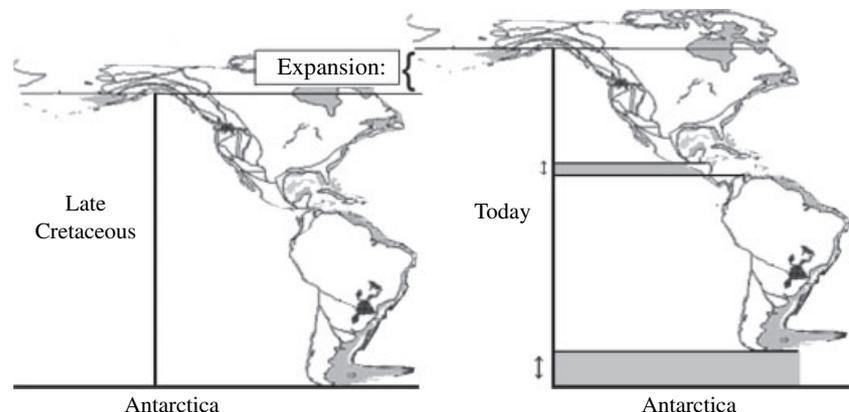


Figure 3 North-south expansion of the Pacific Basin since the Cretaceous. The Americas have separated slightly since the mid-Cretaceous, and South America has drifted away from Antarctica, requiring north-south expansion of the Pacific Basin. The continental figures of Scotese (2001) were used in this figure.

to Antarctica at 80 Ma, the Cretaceous Pacific plate fits relatively snugly in the available Cretaceous Pacific Ocean Basin. This once again implies what all other analyses demand, that the northern part of the Pacific plate and the southern part of the Bering land bridge were near the same relative latitude. Based on PT, the Cretaceous Pacific Basin is believed to have encompassed the Pacific plate and a few other hypothetical oceanic plates, some of which are alleged to have extended 4400–5000 km (i.e., 40–45 latitudinal degrees) north of the Pacific plate (Fig. 2). The geophysical and biogeographical data, however, imply that in the Cretaceous, the Pacific plate and Pacific Basin were the same size and have since increased in length, north to south, by the same amount and at the same time.

CLOSING THE TETHYS AND COMPLETING THE CRETACEOUS CIRCUM-PACIFIC CONTINENTAL CIRCUIT

It is important to note that the Late Cretaceous terrestrial connections linking Eurasia to North America, North America to South America, South America to Antarctica, and Antarctica to Australia are well accepted even in PT (despite what is shown in Fig. 2). These connections constitute more than three-quarters of a mostly circular enclosure of the Pacific, and that alone is suggestive. Since Eurasia and North America comprise a single stretch of continental material and have been so joined since at least the Mid-Cretaceous, this would appear to disallow significant southern motion of Eurasia with respect to North America without evidence of this motion along a major fault. But the boundary between the Eurasian and North American plate, thought to be near the Moma rift in Russia (Gaina *et al.*, 2002), is diffuse. Moreover, the other boundary between the Eurasian and North American plates is the mid-Atlantic ridge (Fig. 1a), which also constrains the motion of Eurasia with respect to North America and permits little relative north–south motion between the two. Finally, as noted, palaeomagnetic data also indicate little relative latitudinal motion between these Laurasian continents since the Late Cretaceous. All this implies that if North America has moved steadily away from Antarctica, then so has Eurasia. Basic geometry would seem to ordain little to no gap among the continents on the west side of the Pacific when the north, south, and east sides delineate a tighter enclosure. Geological and biogeographical evidence linking Australia with East Asia confirms this expectation and completes the terrestrial circuit.

In the 1950s, Warren Carey, an original proponent of Wegener's view of continental mobilism and one of the first to posit subduction and convection as a mechanism for drift, came to realize that Pangean reconstructions were problematic when he could not place India and Australia in their classic Gondwana positions without separating them from the Laurasian regions (Carey, 1988, pp. 158–159). Such a gap, Carey knew, was inadmissible due to geological ties that linked these Gondwanan regions to Laurasia as early as the Palaeozoic. As Carey (1988, p. 161) quotes the father and son geologists (and critics of PT), Howard A. and Arthur A.

Meyerhoff: 'India has been part of Asia since Proterozoic or earlier time. This is a geologic fact, which nothing can change'. Carey attributed his conversion from PT to EE, at least partly, to his eventual discovery that the dubious chasm between Laurasia and the eastern Gondwana regions, India and Australia, resulted from constant radius assumptions and disappeared when the continents were assembled on a smaller globe. Carey, one of the original plate tectonic theorists, never assumed an expanding Earth *a priori*; he felt it was the only feasible geological conclusion. Originally, PT palaeocartographers ignored the Indian and Australian links to Laurasia and simply assumed the existence of a vast Tethys ocean in Carey's unacceptable gap (Fig. 4a, from Barron *et al.*, 1981).

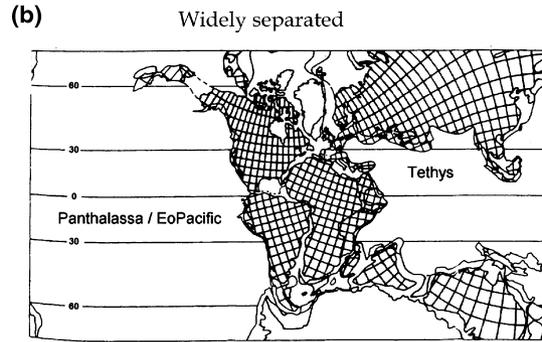
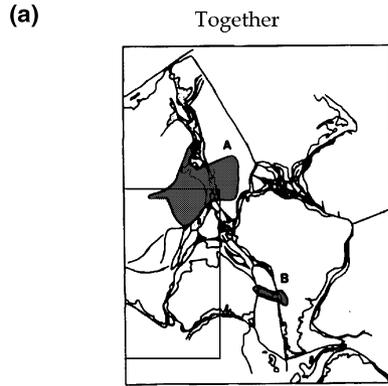
Since that time, Carey's argument that these Gondwanan and Laurasian regions were in proximity in the Palaeozoic, originally dismissed, has now become accepted. Evidence from tectono-stratigraphic, palaeomagnetic, and biogeographical analyses that link India and Australia with southern Asia has become so pronounced that the classic view of PT (Fig. 4a) has now been abandoned. India, Turkey, Iran, Afghanistan, Qiantang, Lhasa, and West Burma, which are juxtaposed today, have ancient ties that confirm their proximity in the Palaeozoic. The same is true for Australia and the Asian regions, Indonesia, Indochina, and China (Metcalf, 1998). At least initially, the implication that these territories have been in proximity since at least the Palaeozoic would seemingly confirm the geological reality of a narrow, epicontinental Tethys and the validity of EE.

PT palaeocartographers, however, have since developed a rather creative solution. Assuming an Earth of present size, PT theorists cannot place India and Australia next to Antarctica and Asia simultaneously, so the latest PT reconstruction (Audley-Charles, 1988; Metcalfe, 1998) breaks off all of southern Laurasia and places it on northern Gondwana. Practically, everything south of and including North China has now become an originally 'Gondwanan' terrane (Fig. 4b). The resulting Palaeozoic depictions of the Southern Laurasian–Northern Gondwanan relationships now resemble the classic EE palaeomaps of those regions detailed by Shields (1979) more than 25 years ago. In PT, all these Gondwana–Laurasian fragments then drifted across the Tethys at some point, followed eventually by India and Australia, which later migrated across the Tethys and reunited with those very same wayward terranes.

Unfortunately, a single relocation of the continental segments can only help explain evidence from one particular era. Thus, PT now must implement the hypothesis that a multiplicity of regions migrated throughout the Palaeozoic and Mesozoic at four different times from India and Australia to their current Asian residence, with each wave of terranes demanding its own spreading centre and its own new and vanished ocean separating them from Australia and India (Fig. 4b–d). In brief, PT theorists, faced with confounding biogeographical and geological data linking India and Australia to Asia in the Palaeozoic, have maintained their first vanished-ocean hypothesis by supposing the existence and disappearance of three more hypothetical oceans – Palaeo-Pacific at first, followed by Palaeo-Tethys, Meso-Tethys, and Ceno-Tethys (Metcalf, 1998).

Expanding earth (Shields, 1979)

Old plate tectonics (Barron et al., 1981)



New plate tectonics (Metcalf, 1998)

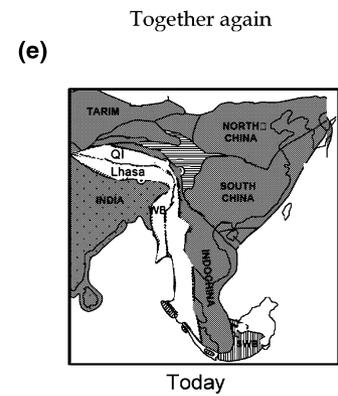
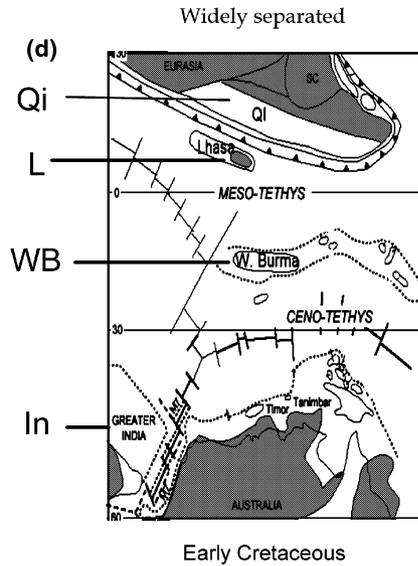
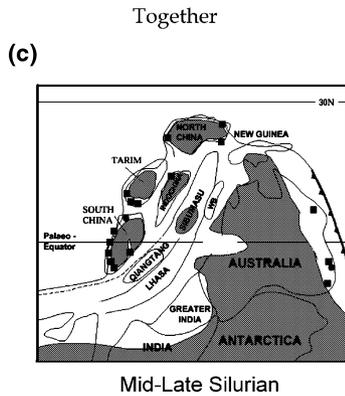


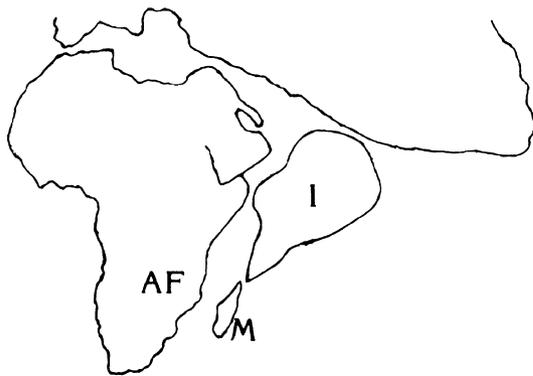
Figure 4 EE Tethys compared to the changing PT views of the Tethys. Figure 4a depicts Shields' EE palaeomap (1979) of the west Pacific and east Tethys. The dark shaded areas connecting East Asia to western North America and east Australia to western South America represent regions that exclusively share a significant number of Early Jurassic and Late Triassic poor-dispersing taxa (Shields, 1998; McCarthy, 2003). The EE view of southern Asia's juxtaposition with India and Australia contrasts markedly with the classic PT view of a single, wide Tethys of Barron *et al.* (1981) (Fig. 4b). PT theorists have now rejected the old PT views and have closed the Tethys between these regions in the Silurian (Fig. 4c) – although in PT another gap is now depicted north of this. According to this new view, Qiantang (Qi), Lhasa (L), West Burma (WB) and India (In) were all together in the Silurian, were greatly dispersed in the Permian to Early Cretaceous (Fig. 4d) and have now all reunited (Fig. 4e). Figures 4c–e, from Metcalfe (1998), have been modified slightly for clarity.

Moreover, according to PT, this collage of regions has managed to dissemble and reassemble, piece by piece, on the other side of these great seas like widely-scattered puzzle pieces randomly reuniting. For example, PT theorists must contend that the various regions of Turkey, Iran, Afghanistan, Qiantang, Lhasa, West Burma and India, which were together in the Palaeozoic and are still together today, were widely separated at various times by three different oceans. Then a repeated pattern of formations and disappearances of spreading centres and subduction zones over the course of hundreds of millions of years erased the interim basins and

neatly reunited the widely dispersed and formerly connected fragments.

Biogeographical data remain problematic, however, for one still finds Asian taxa in India and Madagascar in the Late Cretaceous. The Madagascan titanosaur, *Rapetosaurus krausei*, appears most closely related to the Mongolian *Nemegtosaurus* and *Quaesitosaurus* (Rogers & Forster, 2001). Briggs (2003) cites iguanid lizards and boid snakes that reached Madagascar from Asia. Prasad & Sahni (1988), Prasad *et al.* (1994), and Sahni & Bajpai (1991) have noted that fossils from the Late Cretaceous intertrappean beds of India have definite Eurasian

Another Narrow Tethys
(Briggs, 2003)



Late Cretaceous

Figure 5 This inflated India view is from Briggs (2003), which he used to explain problematic Late Cretaceous biogeographical links among Madagascar, India and Asia.

affinities. These Laurasian-India links include: crocodylians; various forms of the eutherian mammal, *Deccanolestes*; two families of Laurasian frogs, Discoglossidae and Pelobatidae; freshwater ostracods; and charophyte plants.

Despite all these complicated suppositions of terrane motions used to explain Indian ties to southern Asia prior to the Cretaceous, Briggs (2003) narrows the Tethys anyway (Fig. 5) in order to accommodate these distributions that link India with southern Asia in the Late Cretaceous. Note that, similar to the other recently invented narrow-Tethys views illustrated in Fig. 4c–d, Briggs' (2003) depiction is now essentially empirically indistinguishable from the narrow, mostly epicontinental Tethys of EE.

Briggs shrinks the Tethys by supposing a significantly larger India, reasonably justifying this assumption by citing two palaeomagnetic analyses, in which one indicates 'a crustal shortening of 1500 km (Patzelt *et al.*, 1996) and the other 4000 km (Zaman & Torii, 1999)'. Certainly, these Indian and South Asian regions have experienced crustal shortening due to the expansion of the Indian Ocean and the shoving of India deeper into Asia resulting in the collapse of the epicontinental Tethys sea basins and the creation of the Himalayas.

But the site analysed by Zaman & Torii (1999) is not on the Indian plate; it is in northern Pakistan. This and other geological evidence led Zaman and Torii to conclude that in the mid-Cretaceous the unit actually formed part of the Southern Asian margin – not Greater India. In other words, while Zaman and Torii contended that Asia reached southward to this site, which had an equatorial palaeolatitude of 2.2° S to 1.1° N, Briggs was suggesting that Greater India extended northward to this site. This obviously leaves no room for an oceanic gap, just as Briggs correctly claims that the biogeographical data demand.

The same problems arise for Australia and South East Asia, which display terrestrial biotic associations that continued

throughout the Cretaceous and lasted until the mid-Tertiary. As stated by Cogger & Heatwole (1981) and referenced by Cox (1990), agamid, varanid, and scincid lizards; elapid snakes; and diplodactylid geckos arrived in Australia from East Asia by the mid-Tertiary or earlier. Scanlon *et al.* (2003) note that recent fossil discoveries place elapid snakes in Australia by at least the early Miocene and possibly the late Oligocene. More significantly, molecular evidence suggests the Australian and East Asian varanid and agamid lizards diverged at 112 and 150 Ma, respectively, and that Wallace's Line, which serves as an effective barrier to dispersal today, was spanned by non-volant, terrestrial vertebrates prior to the Cenozoic (Schulte *et al.*, 2003). Molecular evidence also indicates the divergence of the purely freshwater Australasian and Asian arowana fishes at 138 ± 18 Ma (Kumazawa & Nishida, 2000). Scott's (1997) cladistic analysis of the vicariance-derived, helicoid land snails implies the East Asian snail separated from its Australian sister during the Late Cretaceous.

Also, Kielan-Jaworowska *et al.* (2002) propose a sister relationship between Jurassic–Early Cretaceous primitive mammals *Shuotherium* from China and Australosphenida from Madagascar, Australia, and Argentina. Australian dinosaurs also appear to be most closely associated with East Asia than with any other region. Examples that support this Asian-Australian dinosaur link include carnosaurs (Azuma & Curie, 2000), protoceratopsians (Rich & Vickers-Rich, 1994, 2003), oviraptorosaurs (Currie *et al.*, 1996; Long & Choo, 1998), dromaeosaurs (Long & Molnar, 1998) and ankylosaurs (Molnar, 1996; Hill *et al.*, 2003). Museum Victoria's website and information sheet on Australian dinosaurs describes the biogeographical problem this presents as follows: 'The fragmentary evidence indicates that Victoria's dinosaurs are more closely related to the dinosaurs of Asia and North America than they are to those of South America. Because Australia, Antarctica and South America were at that time connected and distant from Asia and North America, one would expect just the opposite. Why this is so is one of the major puzzles to be solved about Victoria's dinosaurs'.

Schulte *et al.* (2003) and Macey *et al.* (2000) explain the distributions of agamid and varanid lizards by ferrying them from Australia to Asia on the drifting terranes. Kumazawa & Nishida (2000) also suggest this explanation for the disjunction of freshwater arowana. Macey *et al.* (2000) write: 'One argument used against early vicariance is the presence of early fossils of varanids in Laurasia (see Fuller *et al.*, 1998). However, this evidence can be explained easily by the continual accretion of Gondwanan fragments to the southern margin of Laurasia starting 300 MYBP [References within]'. This explanation is not as simple as implied. Each wave of terranes requires its own ocean, and an Australian departure and Asian arrival time that are as much as *c.* 80 Myr apart. Macey *et al.* (2000) use palaeomaps of Metcalfe (1996) to suggest that one wave of East Asian terranes arrived in Laurasia at 120 Ma and another at 65 Ma. Schulte *et al.* (2003) use these dates as well. According to Metcalfe (1998), the last terranes out of Australia, which met with Asia in the Late

Cretaceous, departed in the Oxfordian of the Late Jurassic (163–156 Ma). The wave of terranes before those, which began arriving in the Early Cretaceous, left Australia in the Late–Early Permian. The long duration of the trips follows from the assumed distance across the Tethys and the relatively slow spreading rate of oceans.

This would demand that every taxon that used the last South East Asian ferry originated in and separated from Australia in the Late Jurassic at the latest. Yet the Australian and East Asian varanids appear to have diverged at *c.* 112 Ma, which is roughly 40 Myr after Australia's last terrane departure. Schulte *et al.* (2003) at one point appear to suggest India as the possible transport vehicle of the lizards, noting divergence times are more compatible with its later separation from Australia. But the sister taxa of the Australian lizards are found in South East Asia, not India. The sister of the New Guinea–Australian agamids is *Physignathus cocincinus* of Indochina and South China. The sister taxon to the entire *Varanus* clade, *Lanthanotus borneensis*, resides in Borneo. And *Varanus olivaceus*, the sister of varanids predominantly from Papua New Guinea and islands east of Wallace's line, occurs in the Philippines. It does not seem particularly parsimonious to invoke a cross-ocean trek by India as explanation for sister taxa shared by the Philippines and New Guinea, regions that are less than 500 km apart at their closest points.

Also, taxa catching the last terrane from Australia would have had to spend many tens of millions of years in island isolation and could not have arrived in Asia until 65 Ma. Scott's (1997) analysis of land snails, however, suggests the Australian and East Asian snails did not separate until the Late Cretaceous. Also, such a late arrival of terranes cannot help explain the dinosaur connection, all of which were in Asia long before 65 Ma and none of which existed in the Late Permian, refuting the possibility that they caught either the last or second-to-last wave of terranes. For example, primitive ankylosaurs appear in North America in the Late Jurassic (Upchurch *et al.*, 2002), which would require that ankylosaurs originated in Australia in the Permian if rafting on terranes is to be used as an explanation for their predominantly Laurasian distribution. Moreover, a molecular analysis by Hugall & Lee (2004) has now challenged the ancient date of agamid divergence, suggesting instead a split at *c.* 30 Ma. Perhaps one could assume much faster spreading rates and more oceans and more waves of terranes, one for varanids, another for agamids, another for land snails, another for freshwater arowana, another for elapid snakes, still more for each kind of dinosaur. But while this may be permissible in PT (if we may assume the formation and demise of four large oceans in the narrow gap between New Guinea and East Asia, why not eight or sixteen?), such *ad hoc* convolutions begin to border the Ptolemaic.

EE avoids these contradictions and complications and predicts the links naturally. The reason why Australia and India display biogeographical and geological links with Asia throughout the Palaeozoic and Mesozoic is because India and Australia were connected to both Gondwana and Asia in the

Palaeozoic and Mesozoic, as the classic palaeomaps of EE originally depicted. Hypothetical oceans have never separated them. The reason why Australia and East Asia share ancient taxa, like snakes, snails, lizards, freshwater fish, and dinosaurs, while its more recent marsupial fauna show obvious signs of isolation is because the water gap between Australia and East Asia has, if anything, become more pronounced since the mid-Tertiary. It has not significantly narrowed. Changes in local sea-level leading to narrower marine gaps and intermittent emergence and submergence of terrestrial connections provide the simplest explanation for biotic commerce among the circum-Pacific continents throughout the Mesozoic and Early Tertiary – particularly between Asia and Australia and between the Americas.

The multiplicity of terrestrial biotic links between Australia and East Asia in the Cretaceous completes the continental circuit around the Pacific. As shown, the distribution of terrestrial Cretaceous taxa, particularly dinosaurs, require land connections between East Asia and North America, North America and South America, South America and Antarctica, Antarctica and Australia, and Australia and East Asia implying a complete terrestrial enclosure of the Cretaceous Pacific Basin by continental material (Fig. 1c). This once again independently confirms what palaeomagnetic, sedimentary, and simple geometric arguments demand (Fig. 2 & 3): the Cretaceous Pacific Basin was significantly smaller, not significantly larger, than the Pacific Basin of today.

GEOLOGICAL CONCERNS

Briggs (2004) has recently detailed certain understandable concerns about the EE view, most of which are primarily geological in nature. For example, he mentioned 'the absence of a drastic fall in sea level since the Triassic that would have been caused by expansion'. But this presumes that the volume of surface water has remained stable for hundreds of millions of years, a notion that underscores the mainstream bias towards staticism in all things planetary – regardless of what is observed. As Briggs' comment implies, EE necessarily requires that the quantity of seawater, like the quantity of surface ocean crust, has been increasing since the Triassic and so predicts an influx of massive volumes of water, a process likely linked to the origins of oceans. This is another prominent prediction that distinguishes EE from PT, and sophisticated measurements have ruled decisively in its favour. According to tidal gauge data observed throughout the twentieth century (Miller & Douglas, 2004), global sea level has been rising 1.5–2 mm year⁻¹. More recent satellite measurements depict a global sea level rise (GSLR) of 3.2 mm year⁻¹ (Cabanes *et al.*, 2001). While for many years researchers had attributed GSLR to temperature and salinity related changes in volume, Miller & Douglas (2004) showed that such volume changes can 'account for only a fraction of sea level change, and that mass change plays a dominant role in twentieth-century GSLR'.

In the most parsimonious explanation in EE, this expansion of the oceans is just the continuation of the process that

originally inundated the Earth's surface. Currently, the mainstream view of seawater origination is controversial, with many crediting volcanic exhalations (Rubey, 1951 and many textbooks on basic geology), others, icy comets. Kerr (1997) and Goldsmith (1997) discussed particulars and problems with this later view. Neither theory is incompatible with EE, and it is unclear why either process would have halted over the last few hundred million years. But the most obvious mechanism for the origin and increase of surface seawater, and the one favoured by EE enthusiasts like Carey (1988), Maxlow (2001), and Ford (1999), are hydrothermal vents. Estimates suggest that the entire volume of the Earth's oceans will pour through vent systems in the next 1 Myr (Perkins, 2001) to 10 Myr. Murakami *et al.* (2002) have also recently discovered that the mantle may contain more than five times the amount of water than the oceans. In brief, we have confirmed evidence for a water-laden source (mantle), a massive influx of seawater (hydrothermal vents), and a corresponding net increase in seawater mass that has been measured every year for more than a century (GSLR).

In the PT view, GSLR is not related to the origin of oceans, the influx of water from the hydrothermal faucets, or the massive reserves of water in the mantle. Instead, it is assumed to flow exclusively from continental sources (Miller & Douglas, 2004). Regardless, the PT hypothesis that the quantity of surface water has remained stable for hundreds of millions of years, despite annual observations of GSLR, is dependent on a variety of assumptions.

Briggs (2004) also suggested that Precambrian and Palaeozoic marine fossils provided evidence for 'extensive oceans'. But all pre-Jurassic marine fossils are found in continental regions; none occur in the Pacific or any other ocean (Kious & Tilling, 1996). This is consistent with the EE prediction that all deep marine environments were epicontinental seas and that all ocean basins were closed pre-Jurassic. Mainstream geologists account for the lack of pre-Jurassic crust and fossils in the ocean basins with the hypothesis that every square metre of pre-Jurassic ocean crust has been subducted in the last 200 Myr (e.g. Oliver & Isacks, 1967; Isacks *et al.*, 1968), taking the marine fossils with them. This is not evidence for a pre-Jurassic superocean; this is simply a *post-hoc* supposition for why we do not find such evidence for a pre-Jurassic superocean.

An oft-mentioned shortcoming of EE is the fact that standard planetary science cannot seem to account for such expansion and that, in the view of many reasonable scientists, significant post-formation dilation of terrestrial astronomical bodies seems impossible. But the riftings, volcanism, massive resurfacings, separation of ancient crust by juvenile crust and other signs of expansion, so evident on Earth, are common throughout this solar system, and planetary scientists have, indeed, been struggling to explain these observations away one terrestrial body at a time. In fact, on one of Jupiter's moons, Ganymede, the evidence of extension is so pronounced and compensating hypotheses of crustal removal so difficult to envision, that post-formation expansion of Ganymede is now

widely accepted. As Prockter (2001) writes: 'The bright terrain formed as Ganymede underwent some extreme resurfacing event, probably as a result of the moon's increase in size'. Collins *et al.* (1999) agree that the formation of the grooved terrain on Ganymede was likely the result of post-formation 'global expansion'.

According to one hypothesis for the cause of Ganymede's dilation (Kerr, 2001), the moon, in the not too distant past, may have received a 'shot of heat', expanding a frozen subsurface ocean and rifting the surface. Ganymede's orbit is currently too circular to allow significant tidal flexing, so, according to the theory, perhaps Ganymede became entangled in a particular grouping with the other Jovian satellites, deforming its orbit into an ellipse. The resulting tidal flexing provided the heat necessary to cause expansion. Afterwards, Ganymede moved past the resonance back into its more circular orbit.

This explanation for the enlargement of Ganymede is obviously hypothetical, and a fan of parsimony might express concern at the effort to explain so many examples of riftings and surface rejuvenation one terrestrial satellite at a time. But the possibility of post-formation expansion of terrestrial bodies can no longer be immediately dismissed. Not only do we now know that it is possible for riftings analogous to those at mid-ocean ridges to be the result of volumetric expansion of planetary bodies, we know that it has already happened in this solar system.

CONCLUSIONS

The preceding analysis suggesting a closed Pacific in the Mesozoic corroborates the recent investigations of a number of biogeographers who have studied a wide variety of trans-Pacific disjunctions and concluded that vicariance was the most preferable explanation (e.g. Ager, 1986; Matile, 1990; Shields, 1998; Glasby, 1999; Glasby & Alvarez, 1999; Heads, 1999; Cranston, 2005; McCarthy, 2003). The timing of Pacific expansion as determined by crustal age also correlates with this biogeographical evidence. All of the problematic disjunctions of extant taxa in the tropical and southern Pacific (e.g. Matile, 1990; Glasby & Alvarez, 1999; Glasby, 1999; Heads, 1999; Anderson, 2000; Pregill & Worthy, 2003) are consistent with divergence during or prior to the Early Tertiary when, according to EE, the tropical and southern Pacific was significantly narrower. As the crustal age data reveal (Fig. 1a–d), the Pacific 'un-zipped' open from north to south, maintaining direct terrestrial connections among South America and Australia and New Zealand into the Cretaceous and remaining a narrow seaway in the south until as late as the Eocene (McCarthy, 2003). In the Late-Jurassic, Early Triassic when the entire Pacific was closed, we find a myriad of problematic disjunctions of terrestrial tetrapods, freshwater fish, and other taxa of limited vagility shared by east Asia and western North America (Shields, 1998; McCarthy, 2003) – regions that are located on the opposite sides of the globe in PT palaeomaps.

Efforts to explain these disjunctions consistent with geological convention include: sweepstakes; cross-ocean dispersal events of narrow-range, poor-dispersing taxa (e.g. the rafting of the Banded Iguana, *Brachylophus*, Cogger, 1974; Pregill & Worthy, 2003; rafting of the flat oyster, *Ostrea chilensis*, O'Foighil *et al.*, 1999); cross-Panthalassa island hopping of thalattosaurs and pistosaurs (Rieppel *et al.*, 2000), cross-Panthalassa seamount hopping of benthic marine fauna (Newton, 1988); and cross-Pangean range expansions of a large number of terrestrial tetrapods, freshwater fish, and plants – obscured by repeated patterns of wide-ranging fossil absences (e.g. Briggs, 2004). These hypotheses are the same as those used by defenders of continental stabilism in the first half of the twentieth century (e.g. Simpson, 1940, 1943) to explain trans-Atlantic fossil disjunctions of the same type of taxa. du Toit (1944) and Wegener (1966; first edition 1912) rejected such explanations as incredible and contended the disjunctions were evidence the Atlantic ocean was closed. History has since sided with du Toit and Wegener (see Nelson & Ladiges, 2001, for an in-depth analysis of past biogeographical arguments). If most scientists now agree that the pre-Jurassic, trans-Atlantic, biotic disjunctions between South America and South Africa are evidence of vicariance, then they must also agree that the same is true for trans-Pacific disjunctions of the same type of taxa (Shields, 1998; McCarthy, 2003).

Regardless of long-standing feuds over dispersal, it would seem difficult to dispute that the hundreds of trans-Pacific taxa cited are more apt to annex regions that are proximal rather than regions on the other side of the world. No matter how committed some may be to using oceanic jump-dispersal to explain every biotic disjunction across the Pacific, biogeographers should at least be able to agree that terrestrial vertebrates find it easier to cross a river than a superocean. So the question of which theory provides the most parsimonious biogeographical explanation is not debatable. Instead, a defender of PT must argue that the geological evidence obliges the supposition of a pre-Pacific superocean and that the attendant hypotheses of ocean-jumping and missing-fossils are the only possible explanations remaining – no matter how improbable they may seem. The case presented here helps show that the geological evidence, far from unequivocally supporting PT, actually reinforces what all the trans-Pacific, and now circum-Pacific, distributions demand: the Pacific Ocean Basin, like the Atlantic and Indian, first started forming in the Mesozoic and has steadily expanded throughout the Mesozoic and Cenozoic.

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BIOSKETCH

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