ELSEVIER

Earth and Planetary Science Letters 205 (2003) 225–237

EPSL

www.elsevier.com/locate/epsl

Slab pull, mantle convection, and Pangaean assembly and dispersal

W.J. Collins *

Department of Geology, School of Environmental and Life Sciences, University of Newcastle, Newcastle, NSW 2308, Australia

Received 24 May 2002; received in revised form 30 September 2002; accepted 30 September 2002

Abstract

Two global-scale mantle convection cells presently exist on Earth, centred on upwelling zones in the South Pacific Ocean and northeast Africa: one cell (Panthalassan) contains only oceanic plates, the other (Pangaean) contains all the continental plates. They have remained fixed relative to one another for $>$400 Ma. A transverse (Rheic–Tethyian) subduction system splits the Pangaean cell. Poloidal plate motion in the oceanic cell reflects circumferential pull of Panthalassan slabs, but toroidal flow in the Pangaean cell, reflected by vortex-type motion of continents toward the Altaids of central-east Asia throughout the Phanerozoic, has resulted from the competing slab-pull forces of both cells. The combined slab-pull effects from both cells also controlled Pangaean assembly and dispersal. Assembly occurred during Palaeozoic clockwise toroidal motion in the Pangaean cell, when Gondwana was pulled into Pangaea by the NE-trending Rheic subduction zone, forming the Appalachian–Variscide–Altaid chain. Pangaean dispersal occurred when the Rheic trench re-aligned in the Jurassic to form the NW-trending Tethyside subduction system, which pulled east Gondwanan fragments in the opposite direction to form the Cimmerian–Himalayan–Alpine chain. This re-alignment also generated a new set of (Indian) mid-ocean ridge systems which dissected east Gondwana and facilitated breakup. 100–200-Myr-long Phanerozoic Wilson cycles reflect rifting and northerly migration of Gondwanan fragments across the Pangaean cell into the Rheic–Tethyian trench. Pangaean dispersal was amplified by retreat of the Panthalassan slab away from Europe and Africa, which generated mantle counterflow currents capable of pulling the Americas westward to create the Atlantic Ocean. Thermal blanketing beneath Pangaea and related hotspot activity were part of a complex feedback mechanism that established the breakup pattern, but slab retreat is considered to have been the main driving force. The size and longevity of the two cells, organised and maintained by long-lived slab-pull forces, favours deep mantle convection as the dominant circulation process during the Phanerozoic.

Keywords: mantle convection; geodynamics; plate tectonics; slab pull; Wilson cycle; Pangaea; supercontinent

1. Introduction

Major progress in understanding mantle dynamics has come from integrated modelling of global-scale geophysical data, including seismic tomography, heat flow, gravity field, plate motion

* Tel.: +61-2-4921 5410; Fax: +61-2-4921 6925.
E-mail address: bill.collins@newcastle.edu.au (W.J. Collins).

0012-821X/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0012-821X(02)01043-9

and dynamic topography [1–5]. This modelling has shown that the Earth loses most of its heat ($\sim$85%) by mantle convection via tectonic plate flow, with only a minor component ($\sim$10%) lost through plume activity [6]. The geoid lows on the planet correspond to long-lived subduction zones [7], suggesting long-term stability of convection cells. Successful prediction of Cenozoic plate motions requires that the total contribution of slab pull to plate driving forces is $>$90%, with the great majority of that force located in the lower mantle [5]. If correct, these geophysical insights imply that tectonic plate flow, once established, may be controlled by slab-pull forces [2], raising the possibility that Pangaean assembly and dispersal is also controlled by slab pull.

This paper combines simple geodynamic principles with recent plate reconstructions [8], using tomographic modelling and the Phanerozoic orogenic record as supporting evidence, in an attempt to reconcile continental drift and plate tectonics with mantle convection. A cornerstone of the model is the protracted evolution of the circum-Pacific orogenic belts, most of which initiated in the Early Palaeozoic [9] above a circumferential subduction zone that exists to the present day. The longevity of the ocean argues for a stable, global-scale, mantle convection cell surrounded by sinking oceanic lithosphere. This circumferential subduction zone has been largely ignored in plate reconstructions, but I suggest that, in concert with the other major subduction system on Earth, it played a major role in controlling the Phanerozoic migration paths of Pangaean and Gondwanan fragments.

2. Plate motion reconstructions: principles and applications

The recent compilation of Phanerozoic plate motions from the *Paleomap Atlas* [8] is used as a basis for plate reconstructions. It is assumed to be correct to a first order, as it is broadly consistent with other recent reconstructions [10–14].

Modifications to the *Paleomap Atlas* (Fig. 1) were made incorporating the principle that ocean-under-continent subduction is the stable, long-term tectonic configuration, based on the long-lived circum-Pacific orogens. There, oceanic plates diverging from the East Pacific Rise are subducting on either side of the Pacific Ocean to produce the present-day circum-Pacific orogenic belts. Convergent margin activity has probably occurred since the Early Palaeozoic, as observed in the North American Cordillera [15], the South American Pre-cordillera [16], the Tasmanides of eastern Australia [17], the eastern Altaids of northern China [18], and the Alazeya arc system of eastern Siberia [19].

Oceanic slabs continue to subduct until continental-scale plates collide, when slab break-off occurs and the slab-pull effect is ultimately lost. However, loss of slab-pull effects may happen much less commonly than generally suspected, for the trench may re-establish outboard after accretion, but the newly subducted oceanic crust will migrate into the same pre-accretion downwelling zone established by viscous propagation of stresses developed during earlier subduction [7,20]. Alternatively, accretion may induce slab flipping, producing a Taiwan-type tectonic configuration where an inboard, ocean-dipping subduction develops, but it is a transient process limited by the dimension of the closing back-arc. Eventually, usually several tens of million years after slab flipping and back-arc crust subduction, the basin finally closes and the inboard arc accretes to the continent, slab break-off occurs, and normal subduction mode of ocean under continent is re-established, but probably in the same downwelling zone.

Re-establishment of normal subduction mode along the pre-established locus supports the view that convergent margins become dormant, are re-used at a later time, and that lithosphere- (and perhaps asthenosphere-) scale weaknesses might survive on time scales of 100 Myr or more [20]. This does not provide a reason for establishment of subduction zones; it merely suggests that once established, they survive as 'long-lived motion guides' [21] which ensure longevity of the mantle convection system.

Continental fragments cannot migrate across the Pacific Ocean where opposed subduction zones exist, but they can migrate across oceans

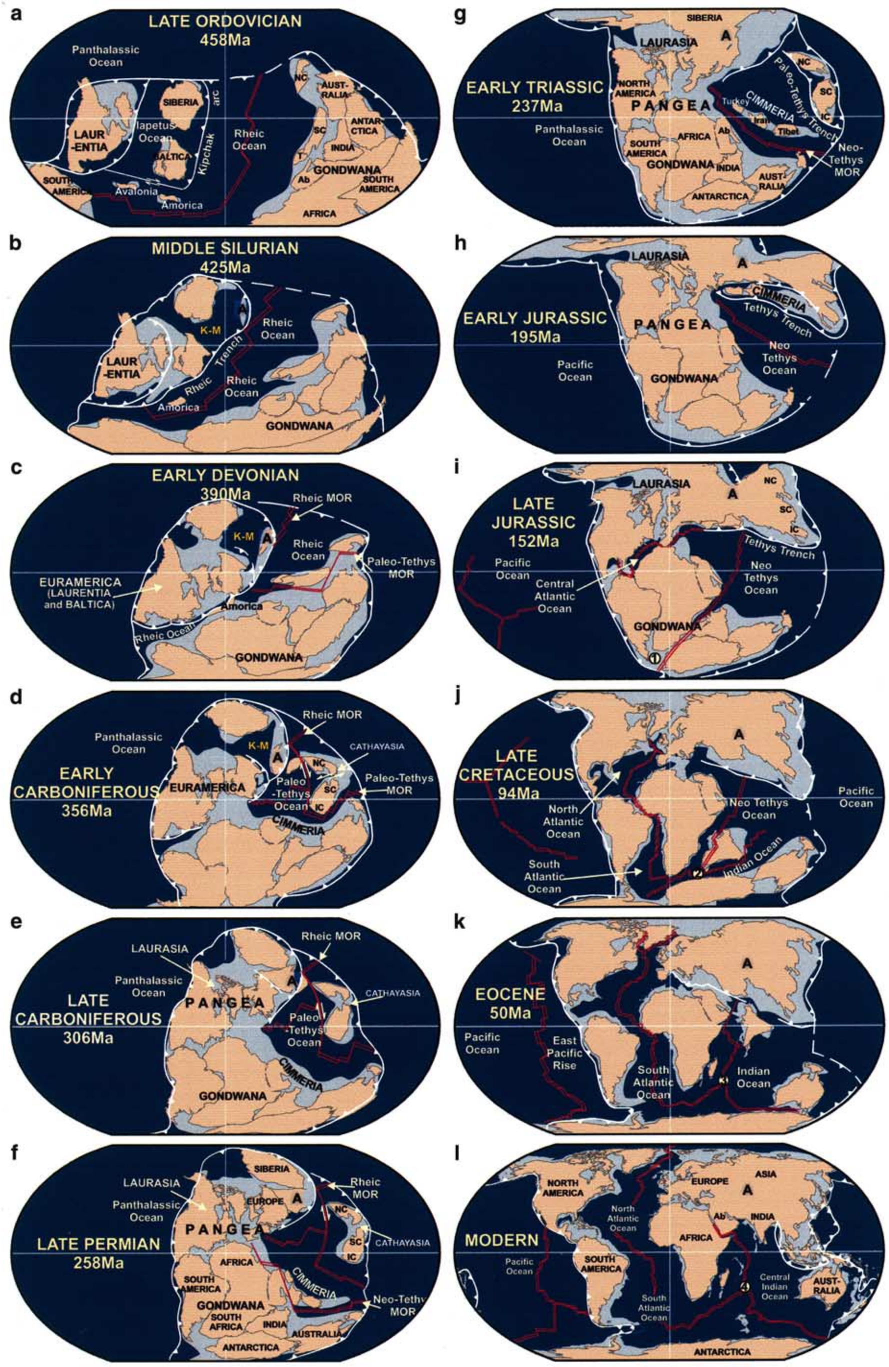

Fig. 1. Phanerozoic plate reconstructions modified from [8,11,23], with addition of MOR systems. A major (Pangaean) cell, bound by a circumferential subduction zone and containing all continents, contracts through the Palaeozoic and expands thereafter. Another (Panthalassan) cell contains exclusively oceanic plates within the Panthalassan/Pacific ocean. A = Altaid collage; Ab = Arabia; IC = Indochina; K-M = Khanty–Mansi Sea [20]; NC = North China; SC = South China; T = Tarim. Numbers 1–4 represent Indian Ocean spreading regimes of [12].

that have only one inboard-dipping subduction system (e.g., Indian House), which will be located along the continental margin where the exotic terrane docks. Docking of large terrane fragments causes ocean closure, such as Iapetus in the Silurian [22] and the Tethyian oceans in the Mesozoic [23]. Accordingly, as Gondwanan terranes have all migrated northward into Laurentia, Pangaea or Eurasia (Fig. 1), the major, long-lived trench systems must have been located adjacent to these continental masses, as we see today with the Alpine–Himalaya system. Transient south-dipping subduction systems might have been associated with slab flipping and back-arc closure during accretion of these terranes, but the long-term subduction direction was northward irrespective of these local boundary complexities. This is consistent with the location of NW-trending high P-wave velocity anomalies beneath the Alpine–Himalayan chain, interpreted as fossil Tethyian slabs [24].

An additional factor controlling destruction of oceans and rates of terrane accretion is the location of mid-ocean ridge (MOR) systems. An active MOR system inhibits destruction of an ocean, for new crust is being simultaneously generated and dispersed away from a subduction zone. However, once the MOR becomes inactive, the diverging oceanic plates fuse and the ocean is rapidly closed by slab pull if only one trench system exists. At this stage, continental fragments (exotic terranes) will rapidly cross an ocean. MOR systems are terminated either by MOR subduction or by generation of a new MOR system, which renders the former MOR inactive, as with the Mesozoic–Cenozoic development of the Indian MOR spreading regimes (e.g., [12]).

A final point, evident from the *Paleomap Atlas* and the reconstructions, is that since the Devonian, new MOR systems seemingly propagate approximately tangentially from the Pangaean subduction system when older MORs subduct along that zone, and all from a similar point near the centre of Fig. 1. This is evident with the Palaeo-Tethys MOR when the Rheic MOR subducted (Fig. 1c), with Neo-Tethys MOR when Palaeo-Tethys MOR subducted (Fig. 1f,g), and probably with the Indian MOR systems when the Neo-Tethyian MOR subducted (Fig. 1i). The fracturing orientation might simply relate to a surface tension effect generated by accommodating sinking rigid plates into a sphere, but the major effect on Phanerozoic Earth was to provide a mechanism for fragmenting Gondwana and facilitating supercontinental dispersal.

3. *Paleomap Atlas* modifications

With the above principles and observations in mind, modifications to the *Paleomap Atlas* [8] mainly follow van Staal et al. [11] for development of the Rheic Ocean in the Early Palaeozoic, and Metcalfe [23] for fragmentation of northern Gondwana and initiation of the ancestral Alpine–Himalayan (Tethyside) collage in the Mesozoic (Fig. 1). The modifications and the geological justifications are:

1. Removal of the inferred south-dipping Early Palaeozoic subduction zones along the north side of Gondwana, because peripheral fragments consistently migrated northward during the Phanerozoic. This is permissive with the geological observations, for only the rifted terranes of northern Gondwana exhibit arc-type volcanism (e.g., Gander and Avalonia), some of which are possibly associated with transient south-dipping subduction [11]. Cratonic Northern Gondwana remained a rifted margin;
2. Inclusion of a major Early to Middle Palaeozoic NW-dipping subduction zone along the SE-Laurentian margin, following [11] (Fig. 1a,b), for this is where Avalonia and Baltica docked with Laurentia to form the Caledonian suture in the Silurian;
3. Inclusion of another W-NW-dipping subduction system behind Baltica, following [11], incorporating the Kipchak arc [25], which linked Baltica with Siberia in the Silurian (Fig. 1b);
4. Extension of the entire subduction system around proto-Pangaea (Euramerica and Siberia) from at least Silurian to Triassic times (Fig. 1b–g). Subduction began along the North American Cordillera in the Ordovician [15] and in northeast Siberia, Silurian–Devonian supra-

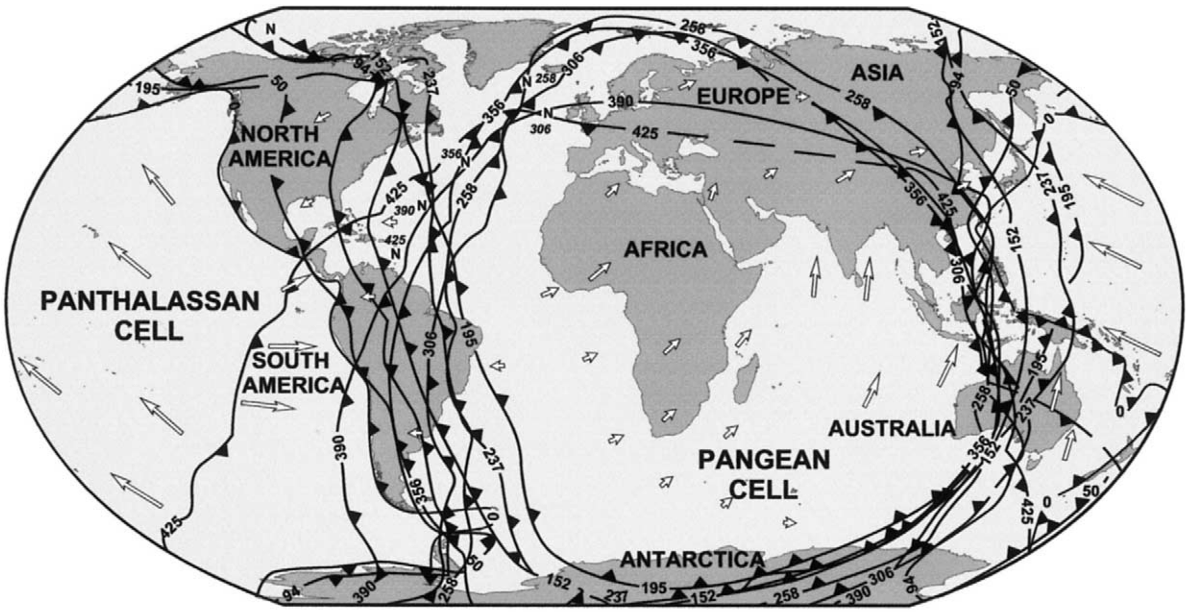

Fig. 2. Location and age (Ma) of Phanerozoic trench systems (adapted from [8]). Solid lines represent active subduction zones; dashed lines represent interpolations between active subduction zones. Also shown are modern plate motion vectors, from [5]. Note stability of trench systems, highlighting long-lived Panthalassan and Pangaean mantle convection cells.

subduction zone ophiolite complexes [26] attest to Palaeozoic convergent margin volcanic activity along the northern margin of Pangaea, which persisted throughout Palaeozoic–Triassic times in the Alazeya arc terrane [19];

5. Laurentia is placed some 60° farther west in the Ordovician (Fig. 1a) and 30° farther west in the Silurian (Fig. 1b), following [11], which is permissive given the lack of longitudinal constraints from palaeomagnetic results, and is consistent with the geological evidence;
6. Addition of a Middle Palaeozoic, Rheic MOR system, required to keep Gondwana separate from Euramerica until the Late Palaeozoic (Fig. 1a,b), as suggested by palaeomagnetic evidence [27]; otherwise, it should have rapidly migrated westward into the Rheic trench;
7. Rapid northward migration of the Tarim block in the Devonian from Gondwana to Kazakhstan (Altaids), based on palaeontological evidence [23], which requires development of a major Palaeo-Tethyian oceanic transform system (Fig. 1d) to avoid contemporaneous northward movement and accretion of Cathayasian blocks with the Altaids.

4. Two mantle convection cells

A relatively simple present-day plate velocity pattern exists on the planet (Fig. 2), showing that all major plates are moving toward the NW Pacific region, except the Americas and Antarctica, a situation that has persisted for the past 200 Myr [5]. Nonetheless, two broad convective cells in the mantle have been recognised as upwelling zones beneath the South Pacific Ocean [28] and east Africa [29], separated by a circum-Pacific annulus of cold downwelling mantle [1,3].

The mantle cell beneath the Pacific Ocean is surrounded by outward-dipping subduction zones (Fig. 2), has a single major MOR spreading system, and contains no major continental fragments. It encompasses approximately half the planet, from the North to South Pole and from the Andes to Indonesia at the equator. The other cell encloses all the continents. Although it has two MOR systems, Atlantic and Indian, it only has one subduction/accretion (Tethyside) system, the Alpine–Himalayan chain (Fig. 3). Throughout the Phanerozoic, one cell occupied the ancient Panthalassan ocean, the other was dominated by

Pangaean supercontinent fragments. To reflect their longevity and character, they are called the Panthalassan and Pangaean cells, respectively. During the Palaeozoic the Pangaean cell contracted, and since then it has expanded (Fig. 1).

The Phanerozoic circum-Panthalassan subduction system has not changed its global pattern in > 450 Myr. Although the precise longitudinal positions of the subduction zones are unconstrained palaeomagnetically, the relative positions are constrained by the dimensions of the supercontinents. Thus, the Early Devonian proximity of Laurentia to Africa constrains the position of Australia and its convergent margin at the eastern limit of Gondwana (Fig. 1c). Similarly, Pangaean linkages throughout the Late Palaeozoic–Early Mesozoic tightly constrain the location of peripheral subduction zones to within ~1000–2000 km (Fig. 1d–i). Thereafter, seafloor magnetic anomalies provide additional constraints on the location of Mesozoic–Cenozoic subduction zones.

5. A Phanerozoic plate coalescence zone

The continents provide a record of global-scale mantle convection (Fig. 3). For example, the Alpine–Himalayan chain shows overall orogen-normal contraction as Africa and India migrate to the northeast and collide with Eurasia. In contrast, the North American Cordillera is characterised by protracted dextral transpression (e.g., [30]), consistent with present plate motions. Similarly, the Mesozoic Tethyside collage of eastern Asia [31] is effectively a 'triple junction' between the Pacific and Pangaean cells where crustal fragments have coalesced.

The major Palaeozoic orogenic collage on the planet is the Altaids [25]. The *Paleomap Atlas* reconstruction [8] shows that the Altaids (A in Fig. 1) drifted several thousand kilometres eastward during the Palaeozoic (Fig. 4a), when Baltica, Siberia and Laurentia all converged on this region as part of Pangaea assembly. South America and Africa show similar Late Palaeozoic convergence toward the Altaids. Since the Palaeozoic, the Altaids path has been a tight eccentric loop, toward which the eastern Gondwanan continents and Africa have converged (Fig. 4b). It is apparent that the Altaids remained virtually stationary as the continents rotated and coalesced about it throughout the Phanerozoic.

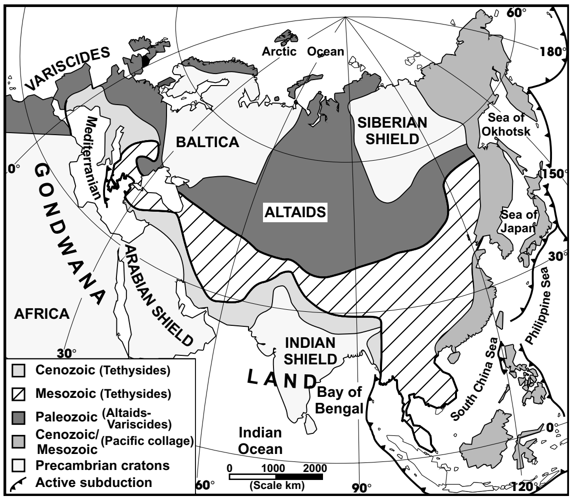

Fig. 3. Map of Eurasia showing location of Phanerozoic orogenic systems. The geometry of the belts implies continental plate convergence toward the Altaids in central-east Asia during and since they formed in the Palaeozoic, ~400 Ma ago (modified from [25]).

6. Pangaean assembly

Convergence of Baltica, Siberia and Laurentia toward the Altaids was the initiation of Pangaean assembly, which coincided with oblique arrival of Gondwana in the Late Palaeozoic (Fig. 4a). Assembly of Baltica and Laurentia to form Euramerica occurred by Silurian closure of the Iapetus Ocean (e.g., [8,11]) and Gondwana and Euramerica collided between the late Early Devonian (e.g., [32]) and Late Carboniferous [27]. Final Pangaean assembly only occurred in the Triassic [8] after piecemeal amalgamation of the east Asian microcontinental fragments (Fig. 1) of Cathayasia (North China, South China, Indochina) and Cimmeria (Tibet, Turkey, Iran).

A digression into nomenclature is necessary here to place Rheic Ocean closure and Pangaean assembly into global context. Various successor oceans to Iapetus have been named, as seaways

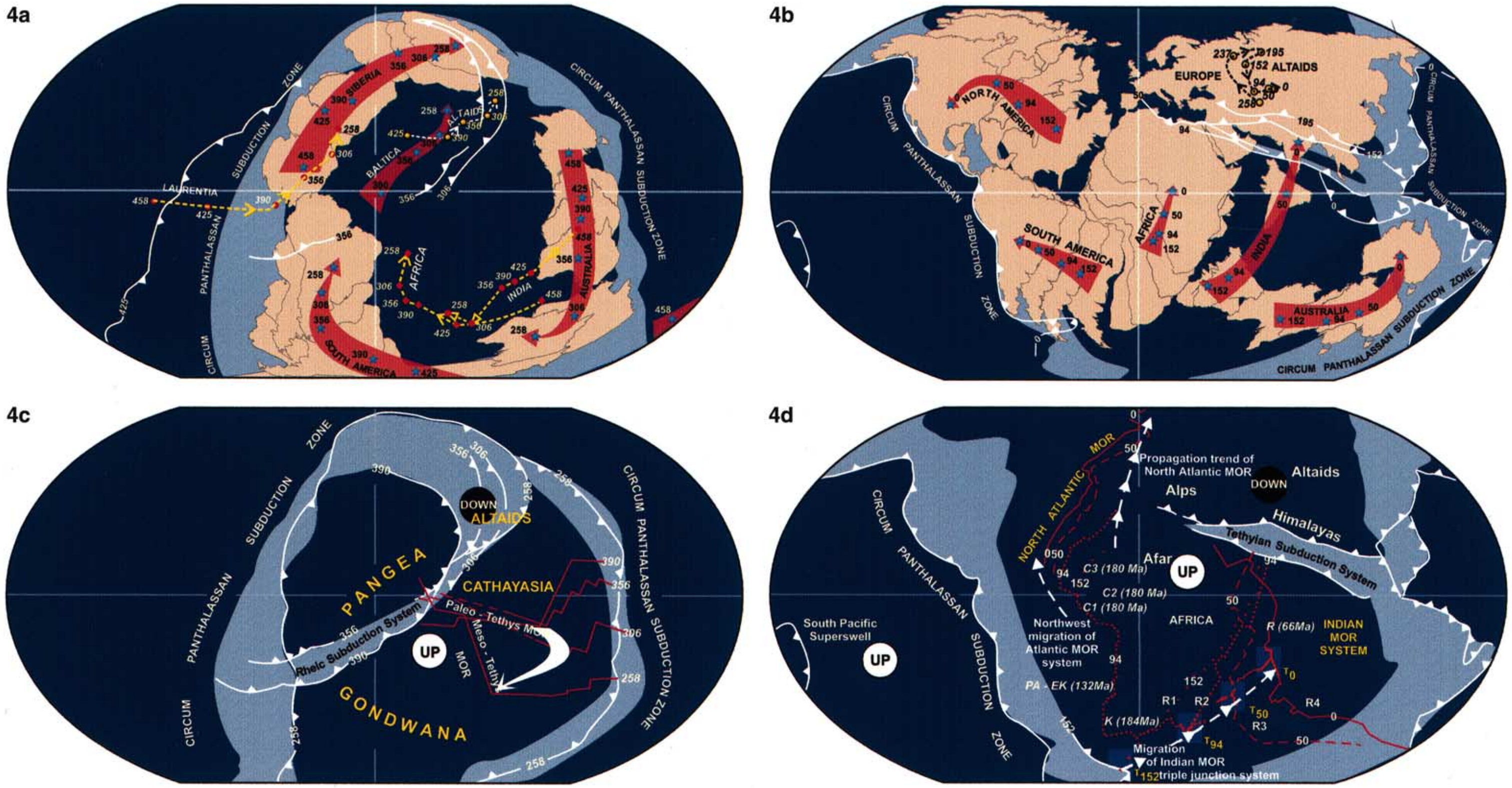

Fig. 4. (a) Continental plate trajectories throughout the Palaeozoic (450–250 Ma) indicate clockwise spiral convergence toward the Altaids, which remain near-stationary. Shaded area shows limit of Palaeozoic Pangaean cell, defined by location of Palaeozoic circum-Panthalassan trenches. Numbers are Ma. (b) Continental plate trajectories throughout the Mesozoic–Cenozoic (200–0 Ma) indicate anti-clockwise spiral convergence toward the Altaids, which remain near-stationary but slightly removed from their Palaeozoic location. Shaded area shows limit of post-Palaeozoic Pangaean cell, defined by location of post-Palaeozoic circum-Panthalassan trenches. Numbers are Ma. (c) Location of Pangaean Palaeozoic subduction zones (heavy lines with barbs directed at upper plate), Tethyian MOR, and upwelling (UP) and downwelling (DOWN) axes. Numbers are Ma. Note progressive shortening and incipient clockwise rotation of subduction zone. Clockwise rotation of MORs is more obvious. C.P.S.Z. = Palaeozoic circum-Panthalassan subduction zone. (d) General location of Pangaean Mesozoic–Cenozoic subduction zones and upwelling (UP) and downwelling (DOWN) axes. Precise location of Tethyian, Indian and Atlantic MORs are also shown, along with relevant hotspots. Numbers are Ma. Note symmetry of North Atlantic and Indian MOR systems. C.P.S.Z. = post-Palaeozoic circum-Panthalassan subduction zone; C1–C3 = Central Atlantic Magmatic Province; K = Karoo; PA-EK = Parana–Etendeka; R = Reunion.

formed when Gondwanan fragments migrated northward during the Silurian–Carboniferous, but from a global perspective, it is clear that a major ocean, which traversed the entire Pangaean cell, gradually shut as Gondwana amalgamated with Euramerica (Fig. 1b–e). Simultaneously another ocean opened to the east as eastern Gondwana travelled southward (Fig. 1c,d). Therefore, it is proposed to simply call the older closing ocean and its associated trench system, Rheic (Fig. 1a–c), and the new opening ocean to the east, Palaeo-Tethys (Fig. 1d–g).

Pangaean amalgamation involved closure of the Rheic and Palaeo-Tethyian oceans, associated with clockwise spiralling of Gondwana about a pole located near the Pangaean cell centre (Figs. 1a–f and 4a). However, the Rheic Ocean did not expand during the southward drift, for the trailing fragments of Gondwana, particularly the Cathayasian blocks, were left behind in equatorial regions as the Palaeo-Tethys MOR system formed in the Devonian (Fig. 1c,d). Final amalgamation of Pangaea and closure of Palaeo-Tethys occurred only after accretion of Cimmerian fragments into Cathayasia [23], following opening of Neo-Tethys in the Late Permian (Fig. 1f), then northward drift of the amalgamated fragments into the Rheic subduction system during the Late Triassic (Fig. 1g,h).

7. Pangaean dispersal

Major Mesozoic Pangaean dispersal involved migration reversal of east Gondwanan continental fragments (Fig. 4b), after the Rheic subduction system re-aligned from NE- to NW-trending, forming the Tethysides trench (Fig. 1i–k). This post-Palaeozoic subduction system, called Tethysides to highlight consumption of the Tethyian oceans [31], involved northward migration and accretion of Gondwanan fragments and destruction of the supercontinent.

Wholesale breakup of Pangaea began in the Jurassic, with propagation of Atlantic and Indian MOR systems on either side of Africa through a series of hotspots (e.g., [33,34]). Initially, the rifts propagated through the Karoo traps and Central Atlantic Magmatic Province at ~180 Ma (Fig. 1i), then through the Parana–Etendeka hotspot at ~130 Ma, isolating Africa and South America from each other and from east Gondwana (Fig. 1j). A new set of Indian MOR systems also tended to migrate through hotspots during the Late Mesozoic–Cenozoic (Fig. 4d), effectively isolating the remaining Gondwanan fragments (Fig. 1i–l), which were subsequently pulled into the Tethyian trench.

Indian MOR triple junctions have migrated systematically northeastward since the Jurassic, in concert with North Atlantic Ocean spreading (Fig. 4d). The northeastward-migrating triple junctions of the Indian system were mirrored by the northwestward migration of the North Atlantic spreading axis. Simultaneously, the Atlantic MOR steadily propagated to the North Pole and will eventually intersect orthogonally with the circum-Pacific trench system in eastern Siberia. This intimate geometric relation between Indian and Atlantic MOR systems, generated approximately orthogonally to the Pangaean and circum-Pacific subduction systems, respectively, began within the vicinity of the Pangaean mantle convection cell centre and has continued to the present day.

8. Geodynamics

8.1. Subduction, spin and supercontinents

Two relatively stationary mantle convection cells, Panthalassan and Pangaean, have controlled plate motions on Earth throughout the Phanerozoic. The cells are broadly outlined by the circum-Panthalassan subduction system, but a transverse Pangaean (Rheic–Tethyside) subduction system splits the Pangaean cell. All continents are confined to the Pangaean cell, constrained by the barriers of subducted Panthalassan lithospheric slabs [1,3], but they have spun relatively freely within, generating the characteristic vortex-type spin of toroidal motion. Whereas the Pacific cell reflects subradial plate divergence and poloidal motion, the Pangaean cell reflects toroidal motion associated with convergence into a major mantle downwelling zone focussed in the east Asian (Altaid) region (see also [35]). The convergence zone is a region where the Panthalassan and Pangaean subduction zones have coincided, effectively a downwelling triple junction of sinking oceanic lithosphere that has produced a major negative geoid on the planet. It coincides with an extensive fast anomaly in the D″ layer, interpreted as a major lithospheric graveyard [35] into which slabs are still sinking [36]. The convergence zones have remained relatively stationary through time and may provide the best approximation for a fixed mantle reference frame on the Earth's surface for the Phanerozoic.

Slab-pull forces acting in concert between the cells controlled Pangaean assembly and dispersal, which is characterised by toroidal motion (Fig. 4a,b). Circumferential slab pull explains radial Panthalassan plate motion, but slab pull into the Rheic trench cannot explain Palaeozoic toroidal motion in the Pangaean cell. Another force is required to explain why the continents tracked along the Panthalassan rim. Given the continents exist on overriding plates virtually unconnected to the subducting Panthalassan plates, the localising force must be viscous propagation of stresses developed in response to Panthalassan subduction, inducing outward-directed counterflow currents in the Pangaean cell (Fig. 5). Thus, while the Rheic subduction zone pulled Gondwana northward to effect Pangaean assembly, the curved trajectory was constrained by the Panthalassan trench system, which acted as a long-term stress guide, causing Gondwanan clockwise motion in the Palaeozoic (Fig. 5a). A similar process of Rheic, then Tethyian, subduction continuously pulled eastern Gondwanan fragments northward in the Mesozoic–Cenozoic to effect supercontinent breakup, but the curved migration paths (Fig. 4b) reflects the modifying slab-pull effect associated with Panthalassan subduction (Fig. 5b).

Re-alignment of the Pangaean subduction system from NE- to NW-trending in the Jurassic, to form the Tethysides trench, also facilitated Gondwanan dispersal by generating a new (Indian) MOR system (Fig. 1i–l). The initial Indian MOR (regime 1 of Reeves and de Wit [12]) rendered the Neo-Tethyian MOR system inactive,

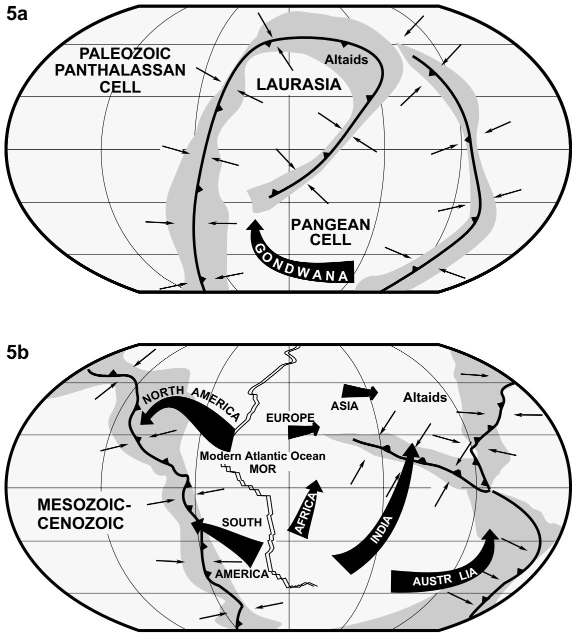

Fig. 5. Highlighted toroidal motion of continents is considered to result from the combined slab-pull force of both long-lived subduction zones, which induced downflow currents below these zones (arrows). Major force on continental plates is the transverse Pangean subduction zone, but trajectories were modified by the long-term stress-guide generated by the circum-Pacific subduction zone.

allowing northward migration of existing Gondwanan fragments. This in turn generated new MORs [12], reflected by the northward generation of successive Indian ridge triple junctions (Fig. 1i–l). As a result, eastern Gondwana was fragmented and India, then Australia, migrated northward into the Tethyian trench.

Northern migration of Gondwanan fragments and successive generation of MOR systems within the Pangaean cell has caused short-term (< 200 Myr) opening and closing of oceans known as the Wilson cycle, and a longer-term > 500-Myr cycle of continent assembly and dispersal. The 150-Myr-duration, Wilson-type cycle of the Caledonides [22] was only a small part of supercontinent assembly. Most Phanerozoic Wilson cycles reflect the dynamics of collisional orogens when continental fragments split from Gondwana and migrated northward to join another continent, all within the Pangaean cell. These collisional orogens, interior to supercontinents, contrast with the peripheral orogens at the external margins of continents [37], which formed along the circum-Panthalassan trench system during the Phanerozoic. Peripheral orogens are typically accretionary in nature rather than collisional, with examples being the North and South American Cordilleras [38] and the Lachlan orogen of eastern Australia [17,39]. Peripheral orogens undergo major contraction and crustal thickening during subduction of active plumes [40] or more generally, by subduction [41] or accretion [42] of oceanic plateaus that emanate from plumes in the Panthalassan cell.

8.2. Upwelling zones and Gondwana breakup

Upwelling zones are located near the centre of the two mantle convection cells (Fig. 4b,d). In the Panthalassan cell, this zone occurs about an axis located near the South Pacific superswell and in the Pangaean cell it exists in northeast Africa, focussed on the Afar plume [29], not as well expressed as the Pacific example and possibly only intermittently developed. From the Middle Palaeozoic, the Pangaean upwelling zone has been the main focus of Tethyian–Indian MOR propagation and rotation, as it is today, and it has been largely responsible for fragmenting Gondwana.

Development of the Indian MOR systems was symmetric with formation of the Atlantic MOR system (Fig. 4d), implying a diminished role for mantle upwelling or hotspot activity as the cause of continental breakup. Although several hotspots lie near MOR triple junctions, the synchronicity and symmetry of Indian and Atlantic MOR development (Fig. 4d) suggests that many of the adjacent Jurassic hotspots were localised by lithospheric stretching during MOR generation, rather than vice versa.

The broad distribution of Jurassic hotspots around Africa supports a model of abnormally hot upper mantle focussed beneath Gondwana at that time. This hot mantle formed beneath the supercontinent by thermal blanketing [43], but it decompressed as the landmass broke up, with resultant basaltic melts rising into major active continental rift zones [3,44], some of which evolved to MORs. Once localised, the hotspots facilitated MOR spreading by thermally softening the extending lithosphere, indicating a feedback mechanism between all processes. Thus, although Pangaean breakup was driven by Pangaean cell dynamics, the warm mantle beneath Gondwana localised breakup by discharging plumes or jets which weakened the extending lithosphere and produced the Jurassic hotspots.

8.3. Atlantic opening and Pangaean cell expansion

Atlantic opening corresponded to retreat of the northern Panthalassan trench system, heralded by a change in migration path of North America in the Permian (Fig. 4a), which coincided with the development of a vast back-arc basin system in the Cordillera [45] and culminated with voluminous Jurassic magmatism [46] and ophiolite development [47] as the Atlantic opened. Outward tracking of the Americas reflects a significant localising force associated with reverse mantle circulation generated by Panthalassan subduction (Fig. 5), which is commonly invoked to explain arc splitting and back-arc formation [48], but these currents must have extended entirely beneath the American continents, otherwise they should have followed Africa toward Asia. This implies that slab retreat has a much greater role in supercontinent dispersal than hotspot development. MOR development may be enhanced by thermal softening of lithosphere at hotspots, but slab retreat at cell peripheries is capable of inducing supercontinent breakup.

If Atlantic opening was associated with expansion of the Pangaean cell during Panthalassan slab retreat, then Panthalassan mantle should flow into the Pangaean cell to conserve mass. Indeed, seismological and geochemical observations have been interpreted as two major outflow zones of Pacific mantle beneath the Caribbean arc of Central America and Scotia arc of South America [49]. Other outflow areas might occur beneath the Mendicino Triple Junction, and perhaps in the Gulf of Alaska. Thus, a mechanism and supporting evidence exist to account for Panthalassan mantle displacement during Mesozoic expansion of the Pangaean cell. It could also explain why

Pacific-type mantle exists beneath the Atlantic Ocean (e.g., [50]).

9. Implications for deep mantle convection

Broad correspondence of the two mantle convection cell centres with the two major upwelling zones (South Pacific and east Africa) on the planet, which apparently emanate from the core–mantle boundary [29], suggests that these large-scale thermal anomalies are fundamentally related to deep mantle convection. This mantle is hotter than global average because it has not been cooled by subduction [28], and it is also the likely region for long-term coalescence of subducted radiogenic crustal material. This general circulation has been recognised previously [35] and also placed within a context of global-scale mantle convective cells [51].

Tomographic evidence shows that some slabs penetrate the 660-km discontinuity (e.g., [4,24, 36]), whereas others are trapped at that boundary (e.g., [35]), which implies that some slabs intermittently subduct through the 660-km barrier. Based on a 25% estimate of the depleted-reservoir size in the upper mantle, Hofmann [50] suggested that a two-layered mantle is the dominant form of convection, although the estimate could be as high as 90% ([50], p. 225). In contrast, based on the tomographic images of deep mantle slabs, on the Earth's excess heat flow budget, and on the long wavelength structure of the lowermost mantle, Kellogg et al. [52] have suggested that subducted material collects in the deep mantle ($\sim$1600 km) above an enriched, dense layer that formed during early Earth differentiation. This more 'holistic' model requires long-term, deep mantle convection.

In conclusion, the existence of two global-scale mantle convection cells, organised and maintained by slab-pull forces at long-lived subduction zones, provides an explanation for the distribution of continents on the planet. Long-term slab pull into these stable subduction zones, located across the Pangaean cell and around the Panthalassan cell, is also capable of explaining Pangaean assembly and dispersal, and provides strong evidence for deep mantle convection operating semi-continuously throughout the Phanerozoic aeon.

Acknowledgements

This work was inspired by reading Geoff Davies' book *Dynamic Earth: Plates, Plumes and Mantle Convection*, which coincided with meeting Chris Scotese and examining his excellent *Paleomap Atlas*. I appreciate the comments of John Ludden and Mary Ford, from the CRPG, Nancy, France, where I undertook sabbatical leave when writing this paper. Martin van Kranendonk and John Veevers also gave useful comments, and Mike Gurnis and Conall Mac Niocaill provided perceptive reviews. Drafting by Steve Dick. Supported by Australian Research Council Large Grant A0001203.***[RV]***

References

[1] P. Olsen, P.G. Silver, R.W. Carlson, The large-scale structure of convection in the Earth's mantle, Nature 344 (1990) 209–215.
[2] G.F. Davies, M.A. Richards, Mantle convection, J. Geol. 100 (1992) 151–206.
[3] D.L. Anderson, Superplumes or supercontinents?, Geology 22 (1994) 39–42.
[4] R.D. van der Hilst, S. Widiyantoro, E.R. Engdahl, Evidence of deep mantle circulation from global tomography, Nature 386 (1997) 578–584.
[5] C. Lithgow-Bertelloni, M.A. Richards, The dynamics of Cenozoic and Mesozoic plate motions, Rev. Geophys. 36 (1998) 27–78.
[6] G.F. Davies, Dynamic Earth: Plates, Plumes and Mantle Convection, Cambridge University Press, Cambridge, 1999, 458 pp.
[7] M.A. Richards, D.C. Engebretson, Large-scale mantle convection and the history of subduction, Nature 355 (1992) 437–440.
[8] C.R. Scotese, Atlas of Earth History. 2001 Paleomap Progress Report 90-0497, Department of Geology, University of Texas, Arlington, TX, 2001.
[9] P.J. Coney, The Lachlan belt of eastern Australia and Circum-Pacific tectonic evolution, Tectonophysics 214 (1992) 1–25.
[10] T.H. Torsvik, J.G. Meert, R. Van der Voo, W.S. McKerrow, M.D. Brasier, B.A. Sturt, H.J. Walderhaug, Continental break-up and collision in the Neoproterozoic and Paleozoic – A tale of Baltica and Laurentia, Earth Sci. Rev. 40 (1996) 229–258.

[11] C.S. Van Staal, J.F. Dewey, C. Mac Niocaill, W.S. McKerrow, in: Lyell: the Past is the Key to the Present, Geol. Soc. Spec. Publ. 143 (1998) 199–242.

[12] C. Reeves, M. de Wit, Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones, Terra Nova 12 (2000) 272–280.

[13] P. Matte, The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review, Terra Nova 13 (2001) 122–128.

[14] G.M. Stampfli, G.D. Borel, W. Cavazza, J. Mosar, P.A. Ziegler, Paleotectonic and paleogeographic evolution of the western Tethys and PeriTethyian domain (IGCP Project 369), Episodes 24 (2001) 222–227.

[15] J.W.H. Monger, J.G. Souther, H. Gabrielse, Evolution of the Canadian Cordillera: a plate tectonic model, Am. J. Sci. 272 (1972) 577–602.

[16] V.A. Ramos, M. Escayola, D.I. Mutti, G.I. Vujovich, Proterozoic-early Paleozoic ophiolites of the Andean basement of southern South America, Geol. Soc. Am. Spec. Pap. 349 (2000) 331–349.

[17] D.A. Foster, D.R. Gray, Evolution and structure of the Lachlan fold belt (orogen) of eastern Australia, Annu. Rev. Earth Planet. Sci. 28 (2000) 47–80.

[18] B.M. Jahn, F. Wu, D. Hong, Important crustal growth in the Phanerozoic: Isotopic evidence of granitoids from east-central Asia, Proc. Indian Acad. Sci. 109 (2000) 5–20.

[19] D.G. Howell, D.L. Jones, E.R. Schermer, in: D.G. Howell, D.L. Jones, A. Cox, A. Nur (Eds.), Tectonostratigraphic Terranes of the Circum-Pacific Region, Circum-Pacific Council of Energy and Mineral Resources, Earth Sciences Series 1 (1985) 3–30.

[20] M. Gurnis, S. Zhong, J. Toth, On the competing roles of fault reactivation and brittle failure in generating plate tectonics from mantle convection, in: M.A. Richards, R.G. Gordon, R.B. van der Hilst (Eds.), The History and Dynamics of Global Plate Motions, AGU Geophys. Monogr. 121 (2000) 73–94.

[21] D. Bercovici, Y. Ricard, M.A. Richards, The relation between mantle dynamics and plate tectonics: a primer, in: M.A. Richards, R.G. Gordon, R.B. van der Hilst (Eds.), The History and Dynamics of Global Plate Motions, AGU Geophys. Monogr. 121 (2000) 5–46.

[22] J.T. Wilson, Did the Atlantic close and then re-open?, Nature 211 (1966) 676–681.

[23] I. Metcalfe, Pre-Cretaceous evolution of SE Asian terranes, in: Tectonic Evolution of Southeast Asia, Geol. Soc. Spec. Publ. 106 (1996) 97–122.

[24] R. Van der Voo, W. Spakman, H. Bijwaard, Tethyian subducted slabs under India, Earth Planet. Sci. Lett. 171 (1999) 7–20.

[25] A.M.C. Sengor, B.A. Natal'in, V.S. Burtmann, Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia, Nature 364 (1993) 299–307.

[26] V.S. Oxman, L.M. Parfenov, A.V. Prokopiev, V.F. Timofeev, F.F. Tretkayov, Y.D. Nedosekin, P.W. Layer, K. Fujita, The Chersky Range Ophiolite Belt, Northeast Russia, J. Geol. 103 (1995) 539–566.

[27] J. Tait, M. Schatz, V. Bachtadse, H. Soffel, Paleomagnetism and Paleozoic paleogeography of Gondwana and European terranes, in: W. Franke, V. Haak, O. Oncken, D. Tanner (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt, Geol. Soc. Spec. Publ. 179 (2000) 21–34.

[28] M.K. McNutt, Superswells, Rev. Geophys. 36 (1998) 211–244.

[29] D. Zhao, Seismic structure and origin of hotspots and mantle plumes, Earth Planet. Sci. Lett. 192 (2001) 251–265.

[30] S.T. Johnson, The great Alaskan terrane wreck: reconciliation of paleomagnetic and geological data in the northern Cordillera, Earth Planet. Sci. Lett. 193 (2001) 259–272.

[31] A.M.C. Sengor, D. Altiner, A. Cin, T. Ustaomer, K.J. Hsu, Origin and assembly of the Tethyside collage at the expense of Gondwana Land, in: Gondwana and Tethys, Geol. Soc. Spec. Publ. 37 (1988) 119–181.

[32] W. Franke, The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution, in: W. Franke, V. Haak, O. Oncken, D. Tanner (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt, Geol. Soc. Spec. Publ. 179 (2000) 63–86.

[33] V. Courtillot, C. Jaupart, I. Manighetti, P. Tapponnier, J. Besse, On casual links between flood basalts and continental breakup, Earth Planet, Sci. Lett. 166 (1999) 177–195.

[34] I.W.D. Dalziel, L.A. Lawver, J.B. Murphy, Plumes, orogenesis and supercontinent formation, Earth Planet. Sci. Lett. 178 (2000) 1–11.

[35] Y. Fukao, S. Maruyama, M. Obayashi, H. Inoue, Geologic implication of the whole mantle P-wave tomography, J. Geol. Soc. Japan 100 (1994) 4–23.

[36] R. Van der Voo, W. Spakman, H. Bijwaard, Mesozoic subducted slabs under Siberia, Nature (1999) 246–249.

[37] J.B. Murphy, R.D. Nance, Supercontinent model for the contrasting character of Late Proterozoic orogenic belts, Geology 19 (1991) 469–472.

[38] P.J. Coney, Circum Pacific tectonogenesis in the North American Cordillera, in: J.W.H. Monger, J. Francheteau (Eds.), Circum-Pacific Orogenic Belts and Evolution of the Pacific Ocean Basin, AGU Geodyn. Ser. 18 (1987) 59–69.

[39] W.J. Collins, Nature of extensional accretionary orogens, Tectonics 21 (2002) 10.1029/2000TC001272.

[40] J.B. Murphy, G.L. Oppliger, A. Hynes, Plume-modified orogeny: An example from the western United states, Geology 26 (1998) 731–734.

[41] W.J. Collins, Hot orogens, tectonic switching and creation of continental crust, Geology 31 (2002) 535–538.

[42] Z. Ben-Avraham, A. Nur, D. Jones, A. Cox, Continental accretion: from oceanic plateaus to allochthonous terranes, Science 213 (1981) 47–54.

[43] M. Gurnis, Large-scale mantle convection and the aggregation and dispersal of supercontinents, Nature 332 (1988) 695–699.
[44] R.S. White, D. McKenzie, Mantle plumes and flood basalts, J. Geophys. Res. 100 (1995) 17543–17585.
[45] R.C. Roback, J.H. Sevigny, N.W. Walker, Tectonic setting of the Slide Mountain terrane, southern British Columbia, Tectonics 13 (1994) 1242–1258.
[46] D.M. Miller, C. Bushby (Eds.), Jurassic Magmatism and Tectonics of the North American Cordillera, Geol. Soc. Am. Spec. Pap. 299 (1995) 425 pp.
[47] R.G. Coleman, Prospecting for ophiolites along the California continental margin, Geol. Soc. Am. Spec. Pap. 349 (2000) 351–364.
[48] W.M. Elsasser, Sea floor spreading as thermal convection, J. Geophys. Res. 76 (1971) 1102–1112.
[49] W. Alvarez, Eastbound sublithospheric mantle flow through the Carribean gap and its relevance to the continental undertow hypothesis, Terra Nova 13 (2001) 333–337.
[50] A.W. Hofmann, Mantle geochemistry: the message from oceanic volcanism, Nature 385 (1997) 219–229.
[51] M. Gurnis, Phanerozoic marine inundation of continents driven by dynamic topography above subducting slabs, Nature 364 (1993) 589–593.
[52] L. Kellogg, B. Hager, R. van der Hilst, Compositional stratification in the deep mantle, Science 283 (1999) 1881–1884.