Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico

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ABSTRACT

Mesozoic rocks of the Baja California Peninsula form a convergent-margin complex that is one of the best-preserved and longest-lived convergent-margin complexes in the world. It shows a three-phase evolutionary trend that we propose is typical of arc systems facing large ocean basins. The trend progresses from phase 1, highly extensional intraoceanic-arc systems, to phase 2, a mildly extensional fringing-arc system, to phase 3, a compressional continental-arc system. This trend is largely due to the progressively decreasing age of lithosphere that is subducted. The modern Earth is strongly biased toward long-lived arc-trench systems, which are compressional, and so evolutionary models for convergent margins must be constructed from well-preserved ancient examples like Baja California.

INTRODUCTION

Mesozoic rocks of the Baja California Peninsula (Fig. 1)[1] form one of the most areally extensive, best-exposed, longest-lived (160 m.y.), least-tectonized, and least-metamorphosed convergent-margin basin complexes in the world. This convergent margin shows an evolutionary trend that may be typical of arc systems facing large ocean basins: a progression from highly extensional through mildly extensional to compressional strain regimes (Fig. 2). In this evolutionary model, subduction is initiated by rapid sinking of very old, cold oceanic lithosphere, but over many tens of millions of years, the age of the lithosphere that reaches the trench and is subducted becomes progressively younger. This causes slab dip to decrease with duration of subduction, resulting in increasingly compressional strain (Jarrard, 1986). A decrease in convergence rate, however, may slow or even reverse this evolutionary trend. In the case of the Baja California margin, convergence rate increased, thus accelerating the proposed evolutionary trend.

In this paper, we present a case study of a long-lived convergent margin, synthesizing published data with our own data. Largely on the basis of our basin analysis studies, we recognize three main tectonic phases in the Mesozoic evolution of Baja California. These are illustrated and described in Figure 2; they include Phase 1, highly extensional intraoceanic arc systems; Phase 2, mildly extensional fringing-arc system; and Phase 3, compressional continental-arc system.

PHASE ONE

The earliest stages of subduction (ca. 220–130 Ma) are represented by intraoceanic arc–ophiolite systems, in which small, steep-sided basins received volcaniclastic detritus. Depositional systems are commonly arc aprons, consisting of pyroclastic and lesser volcanic epiclastic detritus deposited in oceanic intra-arc and back-arc basins (Figs. 1 and 2). The most detailed picture of the facies architecture of a back-arc basin available to date (Marsaglia, 1995) comes from our studies of the Gran Canon Formation on Cedros Island (Fig. 1). The Gran Canon Formation shows a simple, uniform sedimentation pattern that may be typical of back-arc basins isolated from terrigenous sediment influx.

The Gran Canon Formation records the progradation of a thick, deep-marine pyroclastic apron across rifted arc basement onto oceanic crust in a progressively widening back-arc basin. Pyroclastic textures in this apron reflect the growth of the source arc terrane from a deeply submerged chain with little production and dispersal of ash, to a shallow-marine edifice producing hyaloclastic and scoriaceous debris, to an island arc erupting pumiceous differentiated magmas. By analogy with the modern Izu-Bonin arc, an influx of silicic pyroclastic detritus in the upper part of the back-arc apron resulted from caldera-forming eruptions associated with arc rifting. Such an event typically occurs within 10–15 m.y. after the birth of a back-arc basin, and if the rifting ultimately succeeds, the back-arc basin is transformed into a remnant back-arc basin behind a remnant arc. A blanket of silts and sands at the top of the Gran Canon Formation indicates that the arc-rifting event succeeded, leaving the basin separated from the arc by a remnant arc, which was slowly eroded as it subsided to sea level.

PHASE TWO

In the second phase of subduction (Early Cretaceous time, ca. 140–100 Ma), an island arc developed in the present-day western Peninsular Ranges, and an extensional fore-arc basin complex developed outboard of it in the present-day Vizcaino Peninsula (Figs. 1 and 3). We interpret the western Peninsular Ranges island arc to have been a fringing arc that lay at the edge of the continental margin, separated from it by a narrow back-arc basin that received both continental- and arc-derived sediment (Fig. 2). The western Peninsular Ranges island arc was previously interpreted to be an exotic oceanic-arc terrane that was accreted to continental-margin rocks of the eastern Peninsular Ranges in mid-Cretaceous time (Fig. 1). These continental-margin rocks include the Julian Schist, which is interpreted as the fill of a composite (continental to oceanic) extensional fore-arc basin that developed in front of the continental Jurassic extensional arc of California and Arizona (Saleeby and Busby-Spera, 1992). The Julian Schist is now known to occur in both the western and eastern Peninsular Ranges (Fig. 1). This relationship appears to tie the Early Cretaceous arc of the western Peninsular Ranges to the edge of the continent.

The convergent margin was at least mildly extensional in Early Cretaceous time, with well-preserved syndepositional normal faults and high rates of subsidence in both the fore-arc and arc regions (Fig. 2). Convergence was apparently nearly orthogonal at this time (Glazner, 1991). Our data indicate that the margin was non-accretionary, like 45% of all modern convergent margins (Ingersoll and Busby, 1995). Normally faulted crystalline basement extended all the way to the trench (Figs. 2 and 3) Although back-arc and intra-arc extension are widely recognized processes, fore-arc extension is less well understood, even though it has been identified along many convergent margins, both modern and ancient.[2] We suggest that fore-arc extension was more common in the geologic past, when there were more young subduction zones in existence.

Fringing Island Arc

Our studies in a 60-km-long segment of the fringing arc terrane have resulted in recognition of two stages in its evolution: Stage 1 is characterized by intermediate-to-silicic-composition, dominantly explosive volcanism, culminating in

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[1] GSA Data Repository item 9825, references for Figure 1, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

[2] References to papers documenting fore-arc extension are available from the GSA Data Repository. See footnote 1.

Data Repository item 9825 contains additional material related to this article.

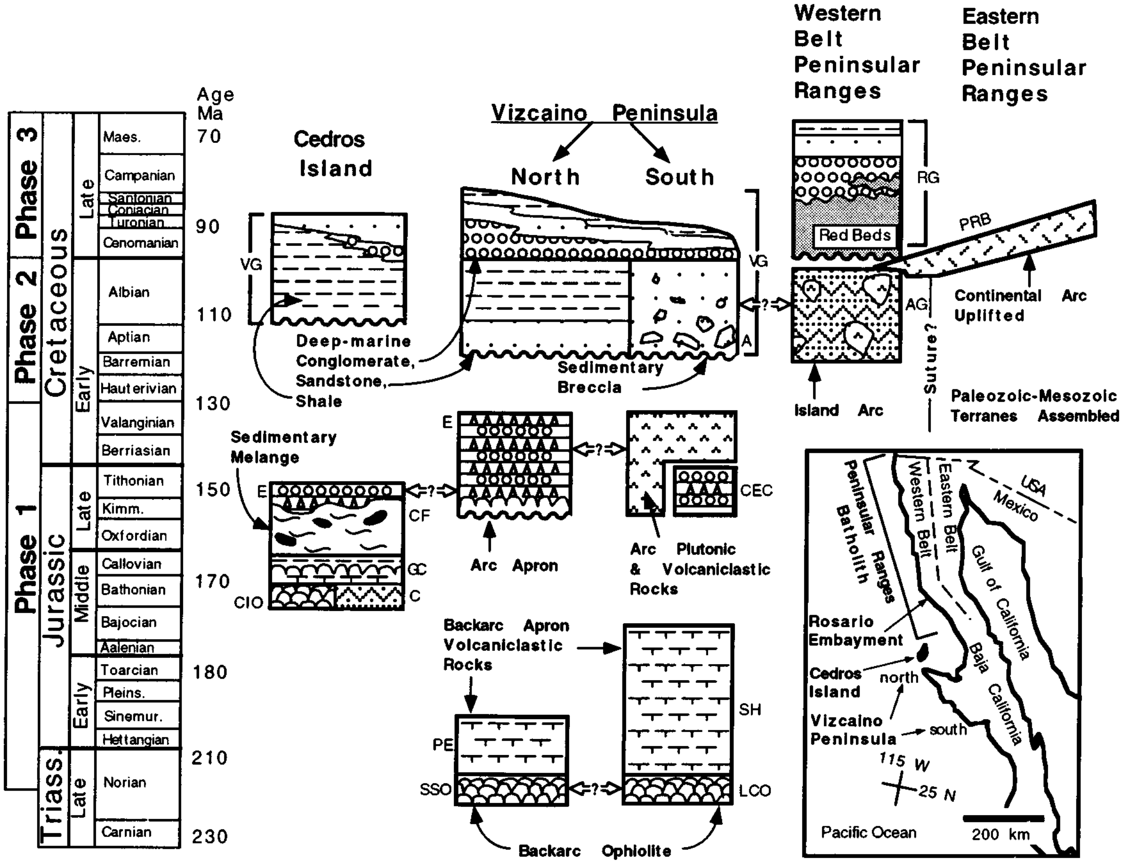

Figure 1. Tectonostratigraphic chart and locations of Mesozoic convergent-margin assemblages in Baja California, Mexico, grouped by evolutionary phases (see Fig. 2). Fuller explanation and sources of data available from the GSA Data Repository. Phase 1: South Vizcaino Peninsula—La Costa ophiolite (LCO), San Hipolito Formation (SH), and Cerro El Calvario volcanics (CEC). North Vizcaino Peninsula—Sierra San Andres ophiolite (SSO), Puerto Escondido tuff (PE), and Eugenia Formation (E). Cedros Island—Cedros Island ophiolite (CIO), Choyal oceanic arc assemblage (C), Gran Canon Formation (GC), Coloradito Formation (CF), and Eugenia Formation (E). Phase 2: Vizcaino Peninsula and Cedros Island—Asuncion Formation (A) and Valle Group (VG). Western Belt Peninsular Ranges—Alisitos Group (AG) and associated back-arc continental-margin assemblages of eastern belt of Peninsular Ranges. Phase 3: Vizcaino Peninsula and Cedros Island: Valle Group (VG). Western Belt of Peninsular Ranges—Rosario Group (RG). Eastern Belt Peninsular Ranges—continental-arc plutons (PRB).

caldera-forming eruptions. Normal faulting resulted in rapid subsidence and produced a rugged fault-controlled morphology prone to large-volume sector collapse. Stage 2 is characterized by mafic-composition, effusive subaerial to deep-water volcanism and widespread diking. This records accelerated arc rifting.

Extensional Fore Arc

Coarse-grained slope aprons developed in the fore-arc region during phase 2, in response to regional extension (Fig. 3). The slope apron deposits built directly from coastal normal fault scarps onto graben floors at bathyal water depths. They are thick, laterally extensive wedges of texturally and mineralogically immature detritus. Although most of the detritus was derived from immediately adjacent basement horst blocks, arc-derived detritus was able to make its way into each sub-basin, suggesting that the grabens stepped down toward the trench (Fig. 3).

PHASE THREE

In the third phase of subduction (Late Cretaceous to early Paleocene time, ca. 100–50 Ma), a high-standing continental arc was established in the present-day eastern Peninsular Ranges (Fig. 2). Although the third phase was part of a gradual trend toward progressively more compressional stress, this trend accelerated in mid-Cretaceous time (ca. 105–95 Ma), as shown by (1) the presence of reverse faults of that age within the arc, and (2) the coeval sudden influx into fore-arc basins of coarse-grained sediment eroded from relatively deep structural levels of the arc (Fig. 1). An increase in plate convergence rate (Engebretson et al., 1985) may have collapsed the fringing arc against the continent and caused the reverse faulting and uplift.

Strongly coupled subduction along the Late Cretaceous compressional arc resulted in (Fig. 2) (1) accretion of blueschist metamorphic rocks, development of a residual fore-arc basin behind the growing accretionary wedge, and development of extensional fore-arc basins atop the subduction complex, and (2) development of fore-arc strike-slip basins on arc basement, due to oblique convergence predicted by the plate reconstruction models of Engebretson et al. (1985) and Glazner (1991). This oblique convergence may have ultimately resulted in the 12 degrees northward displacement of Baja California relative to stable North America proposed by Hagstrum et al. (1985).

Residual Fore-Arc Basin and Trench-Slope Basins

A rapid transition from a mildly extensional arc to a strongly compressional arc is recorded in mid-Cretaceous strata that occur in outboard parts of the fore-arc basin complex (Vizcaino-Cedros region). Gravelly sediment gravity flows with boulders up to 1 m in diameter flooded the entire region, depositing a conglomerate sheet 150–200 m thick overlain by a 2–3-km-thick section of sandstone and conglomerate. Although it could be argued that this flood was the result of resedimentation during a eustatic sea-level drop, the dramatic change in provenance, as well as the great volume, indicates tectonic control. Whereas older fore-arc strata had an undissected arc provenance (i.e., the fringing arc of the western Peninsular Ranges), Cenomanian strata contain abundant plutonic and metamorphic clasts, in addition to silicic volcanic clasts, suggesting derivation from an uplifted, dissected continental arc source (i.e., the eastern Peninsular Ranges).

Detailed studies of the Valle Group on Cedros

Island show that the lower Cenomanian conglomerates were deposited at the onset of extensional brittle deformation of the upper crust concomitant with initial uplift of blueschist-grade rock from great depth (Fig. 2C). The conglomerates fill a deep-marine half-graben structure that formed by reactivation of a Jurassic fault zone (Fig. 4). This Cenomanian fault originated at the rift margin between the arc and the back-arc basin described above under phase 1. The southern block of the basin-bounding fault was downthrown because it was underlain by phase 1 ophiolite, whereas the northern block was underlain by thicker and more buoyant island-arc crust. The axis of the half graben acted as a submarine canyon that funneled sediment gravity flows toward the southwest while the shoulder of the half graben was draped by sandy turbidites and mud (Fig. 4). Further faulting and seismicity resulted in oversteepened and unstable slopes that generated numerous large-scale submarine landslides. These slide blocks were used in a "megaconglomerate" test of paleomagnetic data to prove 12 degrees northward displacement of these strata relative to North America (Smith and Busby, 1993).

Arc Massif Basins

Arc magmatism gradually migrated eastward (inboard) within the eastern Peninsular Ranges during Late Cretaceous time (Fig. 1), so that by Campanian time (or perhaps earlier), the Early Cretaceous arc basement of phase 2 became the substrate for the Peninsular Ranges fore-arc-basin complex.

Our studies demonstrate two lines of evidence for a strike-slip origin of the Peninsular Ranges fore-arc basin complex of Figure 1: (1) kinematic indicators show a strike-slip component for basin-bounding normal faults, and (2) the basin fill shows evidence for rapid alternation of contractional and extensional events—i.e., "porpoising" (Fig. 5)—which is typical of modern strike-slip fore-arc basins (Kimura, 1986; Geist et al., 1988). Strike-slip deformation of the Peninsular Ranges fore-arc caused frequent uplift, subsidence, and tilting events that provided the primary control on the distribution of depositional systems and masked the effects of eustasy. For example, in fewer than 5 m.y. (early Campanian), basal nonmarine strata (Bocana Roja Formation, Fig. 5) were folded and cut by high-angle reverse faults, dropped to bathyal depths (Punta Baja Formation), and then uplifted above sea level, tilted, and weakly folded again (Escarpa Member, Fig. 5). In late Campanian time, normal faults with a right-slip component of displacement caused very high subsidence rates that are a hallmark of strike-slip basins. Shortly before the Campanian-Maastrichtian boundary, the basin was tilted westward so that the eastern margin was uplifted to subaerial environments, passing rapidly westward (basinward) to bathyal depths (Rosario Formation lower sequence, Fig. 5). Finally, contraction of the fore-arc basin in Paleocene time resulted in development of a broad syncline along the axis of the basin, causing incision of the basin margin and resedimentation of conglomerates into the basin axis (Sepultura Formation, Fig. 5)

Fore-arc strike-slip basins in Baja California provide further evidence for the compressional nature of the Late Cretacous arc, as coupling is the primary factor controlling the development of strike-slip faults along convergent margins (Jarrard, 1986).

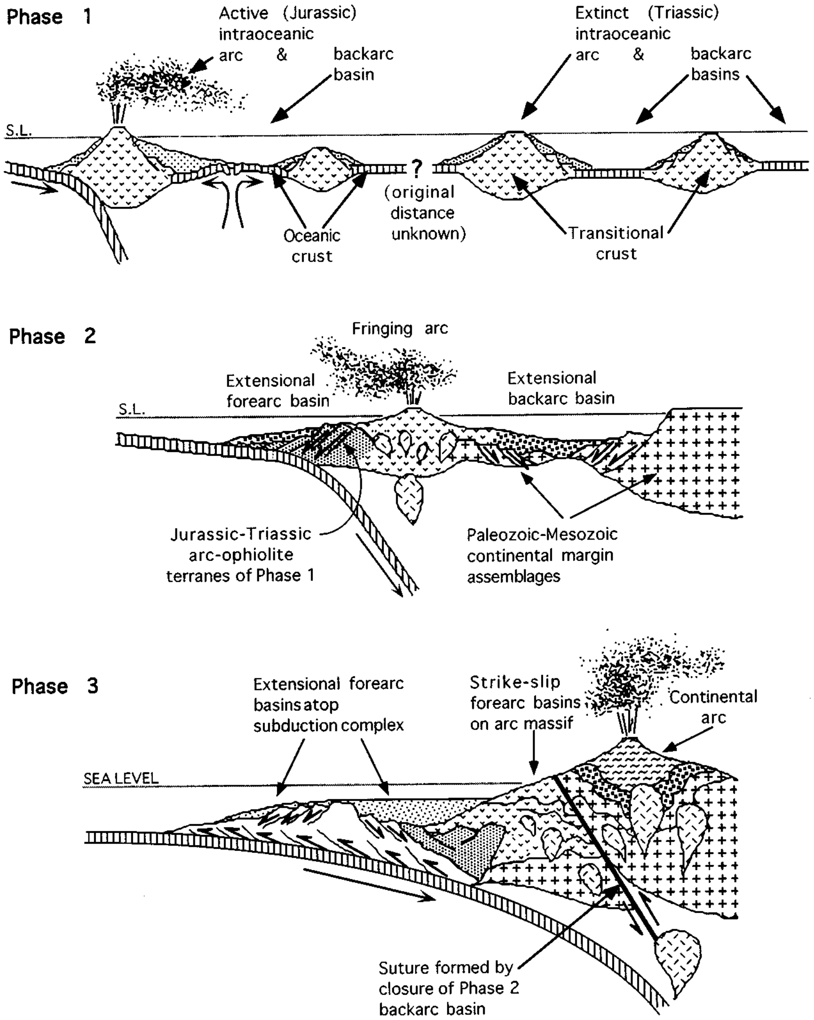

Figure 2. Evolutionary model for arc systems facing large ocean basins: a case study from Baja California, Mexico. S.L.—sea level.

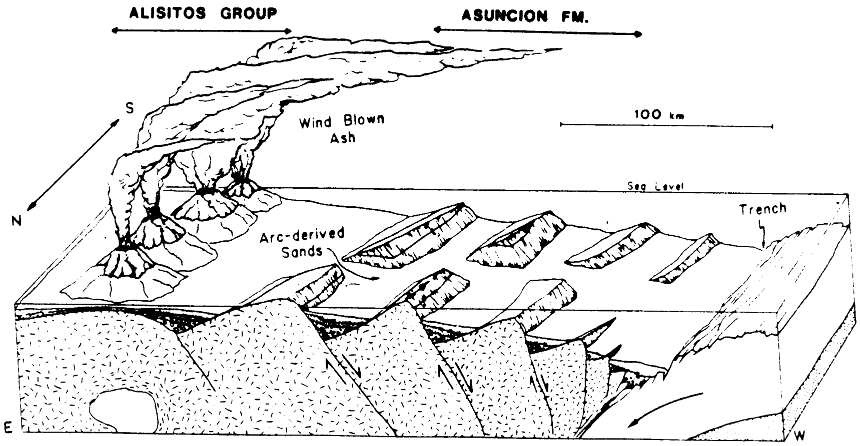

Figure 3. Reconstruction of arc–fore-arc region during phase 2.

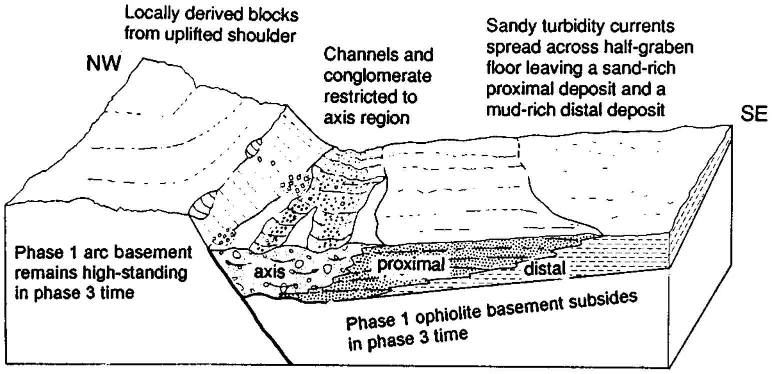

Figure 4. Reconstruction of deep-water extensional fore-arc basin that formed atop accretionary wedge during phase 3.

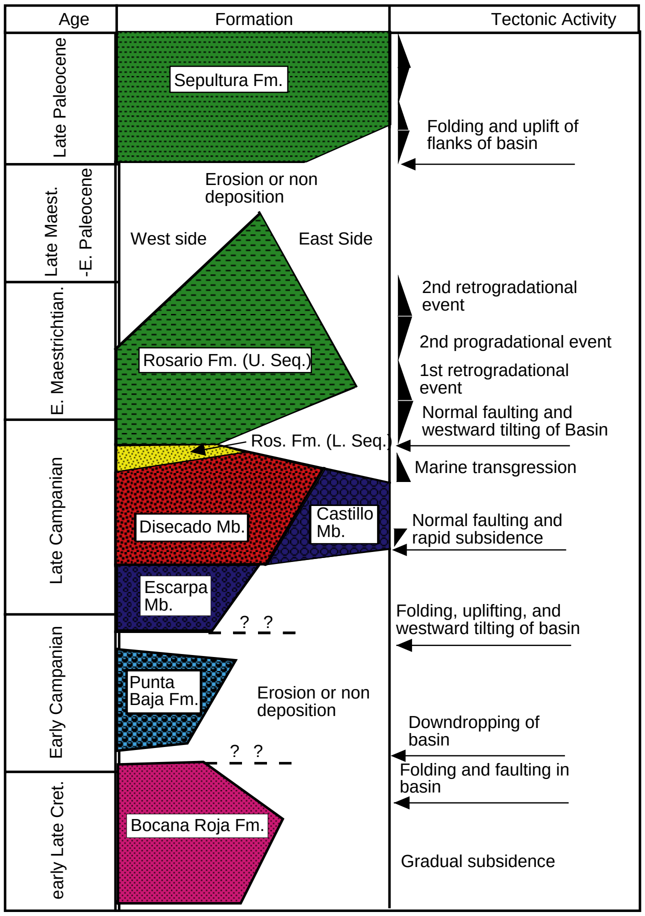

Figure 5. Tectonostratigraphic chart of strike-slip arc-massif fore-arc basin formed during phase 3, showing rapidly alternating contractional and extensional events (Rosario embayment, Fig. 1).

DISCUSSION

Dewey's (1980) kinematic model for arc-trench systems predicted that extensional arcs develop where trench rollback (which is controlled by slab age) is faster than trenchward migration of the overriding plate, whereas compressional systems occur where an overiding plate advances trenchward faster than trench rollback. The dynamic controls on the tectonics of modern arc-trench systems were further examined by Jarrard (1986). He warned that reliable isolation of key variables is precluded by the restricted number of modern subduction zones, but analysis of these suggests that strain regime is controlled by a combination of convergence rate, slab age, and slab dip. Regardless of the dynamic controls, Jarrard's analysis documented a strong positive correlation between the age of a subduction zone and the amount of compressional strain in the overriding plate. Dewey (1980) also predicted that convergent margins should gradually evolve from extensional to compressional. Our work in Baja California confirms this hypothesis, and provides more detailed conceptual models for basin development along convergent margins facing large ocean basins.

The modern world is strongly biased toward compressional arcs because most existing subduction zones happen to be old. For this reason, we need to study the geologic record to learn more about the evolution of convergent margins. Extension characterized the early history of not only the Mesozoic arc of Baja California, but also the Mesozoic arc of the Cordilleran United States and South America. This superregional tectonic regime may have been controlled largely by slab age. We speculate that the paleo–Pacific Ocean basin at the time of breakup of Pangea was composed of very large old plates, resulting in extensional arcs all the way around the paleo-Pacific for at least half of Mesozoic time.

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