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Tectonic lessons from the configuration and internal anatomy of the circum-Pacific orogenic belt

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ABSTRACT

An overview of circum-Pacific tectonic patterns offers three key tectonic lessons.

First, subduction zones of the circum-Pacific and Alpine-Himalayan orogenic belts follow approximate great-circle paths that intersect in the Philippine-Indonesian region, inferentially because a great circle is the shortest distance between two points on a sphere. Consumption of oceanic lithosphere to allow seafloor spreading required for global heat loss therefore encounters least resistance from mantle viscosity and interplate shear when subduction is aligned along a great circle. Reconstructions of ancient orogenic belts can perhaps be improved by the constraint that they also lay along great circles.

Second, circum-Pacific tectonic elements are asymmetric with respect to the rotation pole of Earth. Extensional arc-trench systems with backarc spreading basins are largely restricted to east-facing arc-trench systems of the western Pacific rim, whereas contraction and retroarc thrusting are typical of west-facing arc-trench systems of the eastern Pacific rim. East-west dichotomy of arc-trench tectonics reflects systematic westward drift of lithosphere over asthenosphere due to tidal drag during Earth rotation. This relationship has implications for the interpretation of accreted arc assemblages in the Americas where collision of east-facing intraoceanic arcs with continental margins by closure of remnant ocean basins has been more prevalent than closure of backarc basins behind west-facing, offshore, fringing arcs.

Third, hypothetical coastwise terrane transport along the fringe of the Americas over paleolatitudinal distances suggested to satisfy aberrant paleomagnetic datasets derives from systematic underinterpretation of paleomagnetic vectors. Multiple controlled studies of remanent vectors in sedimentary strata including both marine deposits and continental redbeds indicate flattening factors (f) that range from 0.50 to 0.75, implying inherent discordances of 7.5° to 17.5° in paleolatitude (750 to 1750 km) for mid-latitude (40° to 60°) sites without tectonic transport. Pluton tilt can be expected as a general phenomenon within orogenic belts, and accounts for most aberrant paleomagnetic datasets from Cordilleran intrusions, for which the alternate interpretation of large paleolatitudinal displacement requires the unlikely maintenance of paleohorizontality during tectonic transport over long distances, and also during concomitant or sequential uplift to allow exposure of the plutons by erosion.

Keywords: arc-trench system, circum-Pacific, orogenic belt, tectonic accretion, paleomagnetism

INTRODUCTION

The circum-Pacific orogenic belt is one of the two great orogens of the modern world, the other being the Alpine-Himalayan orogenic belt. For the past 200 million years, circum-Pacific orogenesis has involved subduction of oceanic plates forming the Pacific realm, whereas the Alpine-Himlayan orogen has been constructed as the result of multiple

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continental collisions in the Tethyan-Indian realm during the assembly of Eurasia. The two great orogens intersect in the Philippine-Indonesian region.

The configuration and internal anatomy of the circum-Pacific belt offer three key tectonic lessons outlined in this paper. First, major orogenic belts tend to be aligned along approximate great circles on the globe. Second, there is a fundamental dichotomy between the tectonic behavior of east-facing and west-facing arc-trench systems that reflects systematic westward drift of lithosphere over asthenosphere. Third, paleomagnetic data bearing on paleolatitudinal transport of tectonic terranes must be interpreted with attention to the effects of compaction flattening and pluton tilt. These insights have direct implications for understanding circum-Pacific evolution, but can also be exploited for improved interpretations of ancient orogens.

GREAT CIRCLE OROGENS

Inspection of Mercator and related projections of the circum-Pacific orogenic belt has led to the vision of a "ring of fire" forming the Pacific rim and girdling an enclosed Pacific domain. In actuality, however, the "ring" is a global great circle (Fig. 1), and the "enclosed" Pacific domain is a huge domical feature forming nearly half the world. The circum-Pacific "ring of fire" simply bounds the hemispheric Pacific domain. The Alpine-Himalayan orogenic belt lies along another great-circle path which intersects the circum-Pacific orogenic belt in the Philippine-Indonesian region (Fig. 2). Both orogenic belts are broad and internally complex in detail, but from a global perspective form narrow bands separating non-orogenic continental blocks and oceanic basins. In the Melanesian region, the circum-Pacific trend is displaced or offset along the Alpine-Himalayan trend, and the Australian continent lies within the Pacific hemisphere (Fig. 2).

Recognition that the circum-Pacific and Alpine-Himalayan orogenic belts lie along global great circles is rarely discussed, but was inferred a century ago from earthquake epicenters by de Montessus de Ballore (1903), highlighted at mid-century by Wilson (1950), resurrected later in a plate context by Dickinson (1978), and shown in graphical format by Dickinson et al. (1986). The geologic history of the two belts implies that both have maintained approximate great-circle configurations since their inception at the breakup of Pangea (Fig. 3). Unless the modern world is tectonically anomalous, strong inference (Platt, 1964) implies that ancient orogenic belts also followed great-circle paths.

Incorporation of the great-circle constraint into paleotectonic reconstructions can perhaps improve understanding of geologic history by indicating clear choices between alternate configurations of major orogens permitted by ambiguous paleomagnetic and imprecise paleogeographic constraints. The approach seems viable for the Paleozoic world in which the Gondwanide orogen (Fig. 4) was the circum-Pacific analogue subducting Panthalassan oceanic lithosphere, and the Hercynian orogen with its Appalachian-Ouachita extension was the Alpine-Himalayan analogue along which Laurasia and Gondwana were progressively conjoined to form Pangea. Application of the great-circle constraint to Precambrian orogens has not yet been attempted, but systematic appraisal of alternate tectonic configurations for postulated orogenic belts of Precambrian age is now within the reach of computer-assisted analysis.

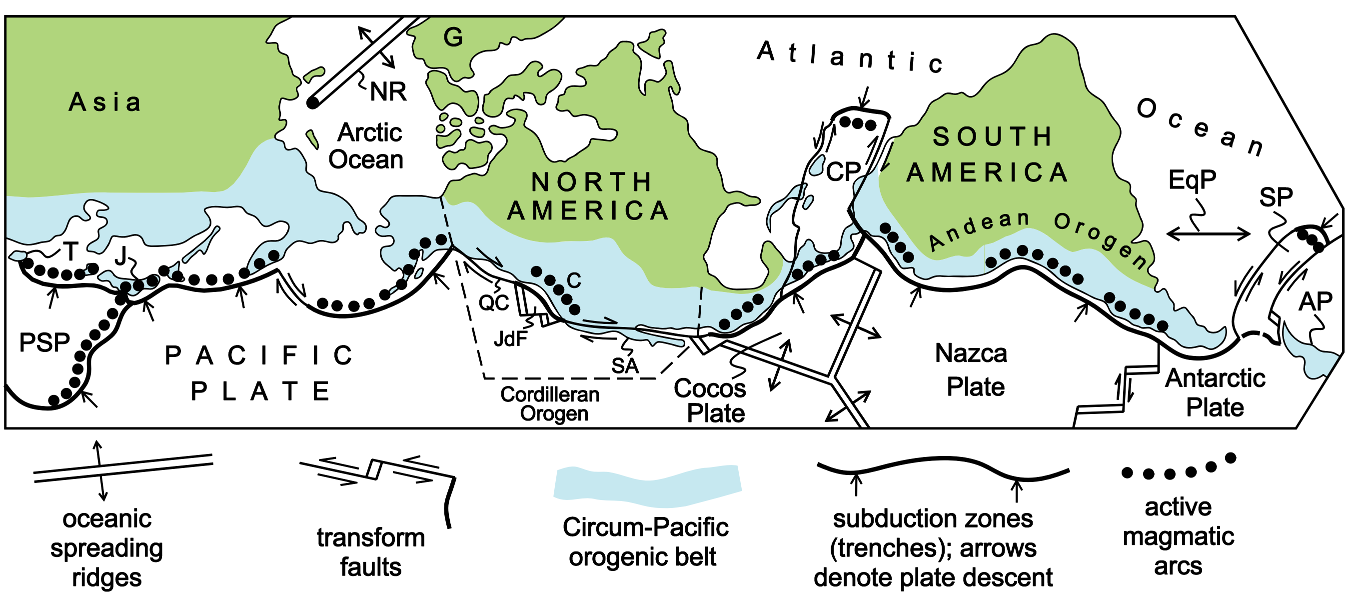

Figure 1. Great-circle view of circum-Pacific orogenic belt (EqP, equatorial plane of Mercator projection): AP, Antarctic Peninsula; C, Cascade volcanic chain; CP, Caribbean plate; G, Greenland; J, Japan; JdF, Juan de Fuca plate; NR, Nansen Ridge; PSP, Philippine Sea plate; QC, Queen Charlotte transform; SA, San Andreas transform; SP, Scotia plate; T, Taiwan.

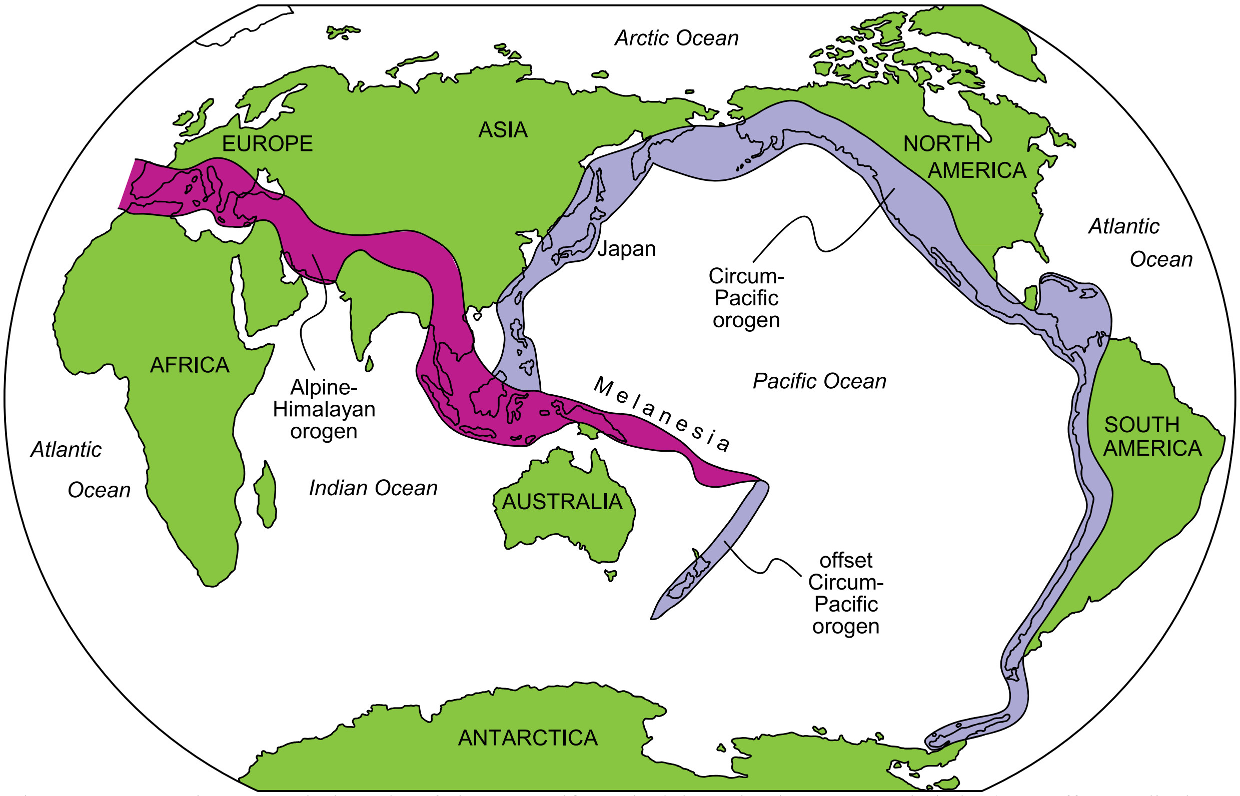

Figure 2. Intersecting great-circle paths of circum-Pacific and Alpine-Himalayan orogenic belts (note offset or displacement of circum-Pacific trend along Melanesian segment of Alpine-Himalayan trend).

A rationale for major orogens to lie along great-circle paths is derived from the following logic. First, disposal of surficial plates by subduction into the mantle is required to allow seafloor spreading elsewhere to dissipate internal heat. Second, plate subduction is resisted by some combination of mantle viscosity and interplate shear. Third, those forces resisting subduction are both proportional to length of subduction zone. Therefore, subduction systems controlling orogenesis will tend to adopt or evolve into great-circle paths because a great circle is the shortest distance between any two points on a sphere. For a given direction and rate of subduction, the area of plate consumed is the same whether an orogen is a great circle or has some other more complex configuration, with the former consequently preferred.

EAST-WEST TECTONIC DICHOTOMY

Multiple marginal seas with backarc spreading centers adorn the western Pacific rim behind east-facing island arcs (trench to the east), but are absent from the eastern Pacific rim dominated by west-facing magmatic arcs (trench to the west) along American continental margins. Backarc spreading centers are present, however, behind the east-facing Lesser Antilles and Scotia arcs which span, respectively, between North and South America and between South America and Antarctica. Seafloor spreading behind west-facing island arcs is restricted to the Andaman Sea, a rhombochasm in

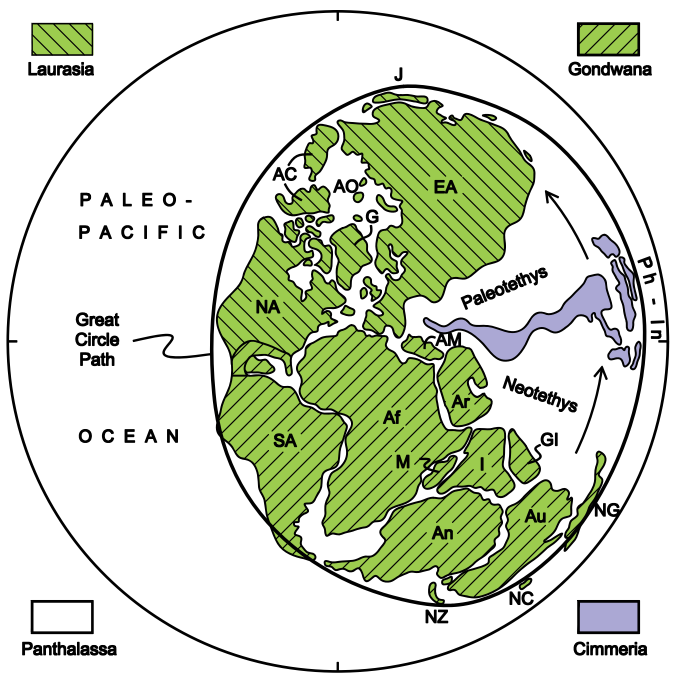

Figure 3. Great-circle path of incipient circum-Pacific orogenic belt along margin of Pangea: AC, Arctic Alaska–Chukotka; Af, Africa; AM, Asia Minor; An, Antarctica; AO, Arctic Ocean; Ar, Arabian Peninsula; Au, Australia; EA, Eurasia; G, Greenland; GI, Gondwanan India (now subducted beneath Tibet); I, Indian subcontinent; J, Japan; M, Madagascar; NA, North America; NC, New Caledonia; NG, New Guinea; NZ, New Zealand; Ph-In, Philippine-Indonesian archipelagoes; SA, South America

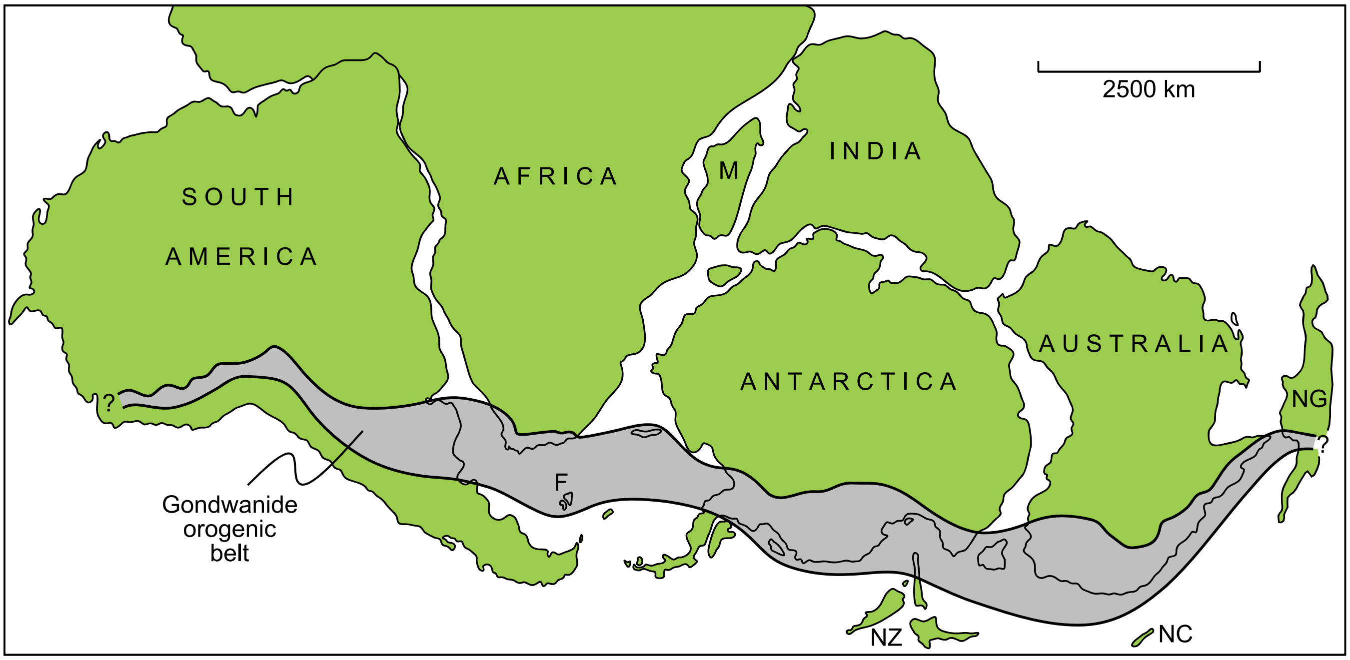

Figure 4. Sketch map of Paleozoic Gondwanide orogenic belt adapted from various sources; F, Falkland Islands; NC, New Caledonia; NG, New Guinea; NZ, New Zealand.

which the spreading direction is oriented subparallel to the Andaman-Nicobar island chain north of Sumatra, and the North Fiji Basin in which the spreading center subparallel to the Vanuatu or New Hebrides island arc is the extensional boundary between Pacific and Indo-Australian plates within a region of intricate plate configurations (Dickinson, 2006).

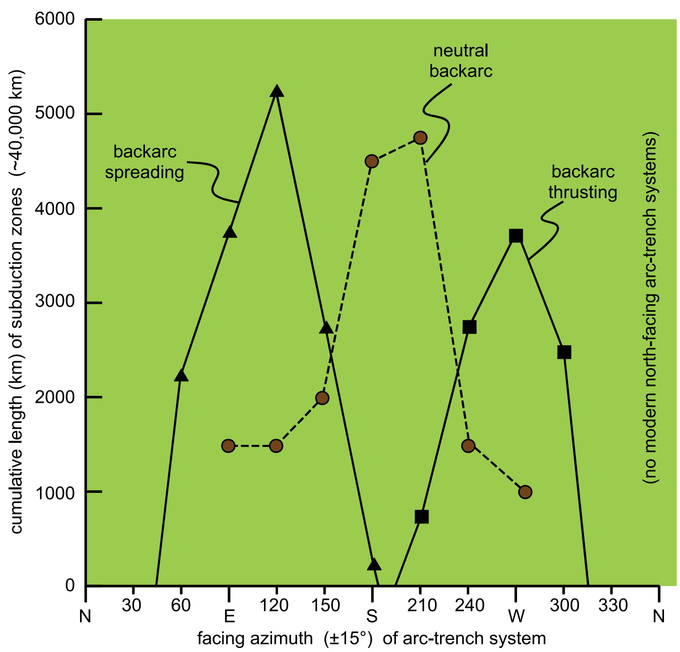

Figure 5. Global assessment of facing direction (azimuth toward trench normal to arc) of segments of arc-trench systems displaying backarc spreading, backarc thrusting, and neither (neutral backarc); revised after Dickinson (1978).

Figure 5 presents in graphic form a global census of the tectonic behavior of arc-trench systems facing in different directions around the Pacific rim, within the Mediterranean Sea, and along the Alpine-Himalayan belt north of the Indian Ocean. The facing azimuths plotted are the directions normal to the arcs toward the trenches. Backarc spreading is restricted to east-facing arc-trench systems, whereas backarc thrusting is restricted to west-facing arc-trench systems. Tectonically neutral arc-trench systems, displaying neither backarc spreading nor backarc thrusting, are most commonly south-facing, but there are currently no active north-facing arc-trench systems. The plot implies that the east-west dichotomy in arc-trench tectonics, with backarc spreading and backarc thrusting characteristic of opposed arc-trench facings, is not merely statistical but globally systematic.

The east-west tectonic dichotomy can be attributed to systematic westward drift of lithosphere relative to asthenosphere as tidal drag gradually slows bulk Earth rotation by differential torque across the "dash pot" formed by rheologically fluid asthenosphere (Scoppola et al., 2006). Overriding lithosphere pulls away from the anchor of subducted slabs for east-facing arc-trench systems, to foster backarc spreading in the wake of retreating lithosphere, but presses against the subducted anchors for west-facing arc-trench systems, to suppress any tendency for backarc extension and to promote backarc thrusting within the overriding plate. Slab dip is typically steeper for east-facing arc-trench systems where backarc lithosphere moves westward away from subduction zones, and shallower for west-facing arc-trench systems where backarc lithosphere advances westward toward and over the subduction zones (Dickinson, 1978; Doglioni et al., 1999), with no general correlation of slab dip with slab age (Cruciani et al., 2005).

Arc accretion

The flanks of the North and South American Cordilleras expose belts of Mesozoic-Cenozoic accreted arcs along their Pacific margins (Fig. 6), but the origins of the accreted arc assemblages are contentious. Many have been interpreted as fringing arcs that originated as west-facing arcs beyond marginal seas that flanked the Americas, but that hypothesis is non-actualistic given the east-west dichotomy of modern arc-trench systems. Accretion of the fringing arcs to the nearby continental margins is ascribed to "accordion" tectonics (Churkin, 1974), a concept devised to provide a rationale for the incorporation of fringing arcs into continental margins by the collapse of marginal basins. The alternative is to infer that the accreted arcs were exotic, east-facing, intraoceanic arcs that accreted to the continental margins through closure of remnant ocean basins by subduction along approaching flanks of the island arcs as well as along the continental margins (Moores, 1998; Moores et al., 2002). This hypothesis is actualistic with respect to relations of arc-trench systems in the modern world.

Figure 7 indicates schematically the contrasting juxtapositions of different kinds of tectonic elements of varying ages expected from accretion of exotic intraoceanic arcs by arc-continent collision (upper panels) or of fringing arcs by accordion tectonics (lower panels). The accordion scenario has alternate variants depending upon whether the marginal basin closes as a result of renewed subduction along the continental margin formed by the arc rifting that led to formation of a marginal basin, or by polarity reversal of the fringing arc to subduct the floor of the marginal basin along its seaward side. In either case, a relict forearc belt is present along the seaward flank of the orogen after the fringing arc is incorporated into the continental margin. For the scenario of exotic arc accretion, forearc belts are incorporated into a deformed suture zone within the orogen, and no relict forearc belt is present along the seaward flank of the expanded orogen.

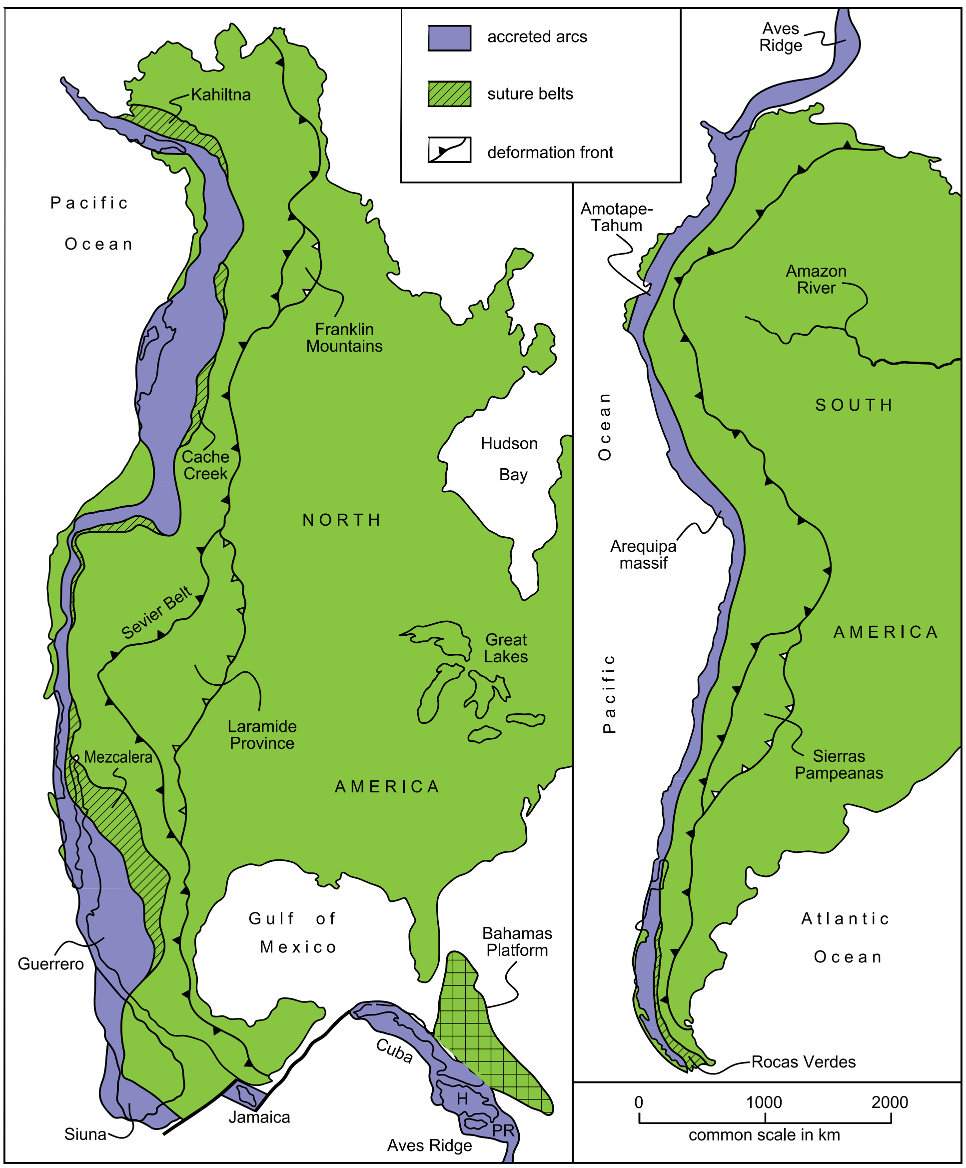

Figure 6. Coastal belts (blue) of accreted Mesozoic-Cenozoic arc assemblages in the American Cordilleras; H, Hispaniola; PR, Puerto Rico.

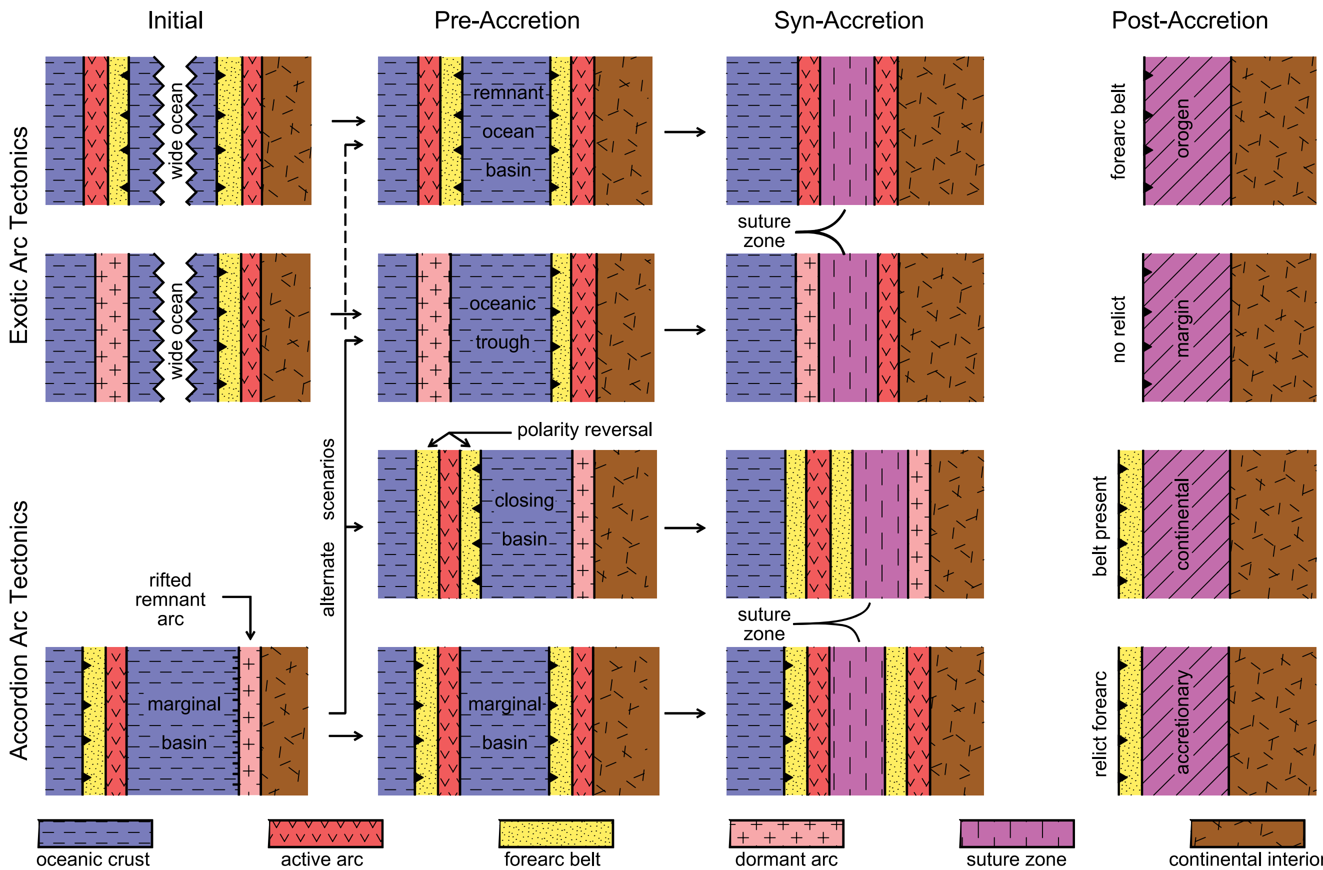

Figure 7. Tectonic elements of arcs accreted to continental margins by different plate interactions during orogen evolution (note contrasting patterns of forearc belts for different tectonic scenarios).

American margins

Mesozoic-Paleogene collisions of exotic intraoceanic island arcs with the Cordilleran continental margin are (a) generally accepted with various caveats for Canada (Dickinson, 2004); (b) argued for, though not universally accepted for, the USA (Dickinson, 2008) and Mexico (Dickinson and Lawton, 2001); and (c) well documented for the Mesoamerican region including both the Caribbean arena (Pindell and Barrett, 1990; Pindell et al., 2005) and the Colombian-Equadorian Andes (Bourgois et al., 1987; Lebras et al., 1987; Jaillard et al., 1997; Cosma et al., 1998; Reynaud et al., 1999; Hughes and Pilatasig, 2002; Kerr et al., 2002), but (d) doubted for Peru and Chile farther south (Ramos and Aleman, 2000). Accretion of exotic arcs extended at least as far south as the Amotape-Tahuin terrane (Fig. 6) near the Ecuador-Peru border (Mourier et al. 1988a, 1988b; Pecora et al., 1999; Vallejo et al., 2006), but exotic tectonic elements have not been identified farther south. As it seems unlikely that arc accretion by arc-continent collision would progress for 12,500 km along the margins of North America and Mesoamerica, but not for the additional 5000 km of continental margin southward along the edge of South America, appraisal of geologic relations and geodynamic interpretations for coastal Peru and Chile may need reconsideration.

In Peru, for example, the so-called marginal basin into which the Late Cretaceous coastal batholith was emplaced (Pitcher, 1978) contains 9000 m of basic volcanic and volcaniclastic strata of Early Cretaceous age including pillow lavas and ribbon cherts (Atherton et al., 1983, 1985). Although the basin is commonly interpreted as an ensialic extensional basin formed in place within the continental margin (Atherton and Webb, 1989), the lithofacies are suggestive of an accreted oceanic assemblage (as depicted on Figure 6). Deposition of the thick volcanogenic succession is commonly inferred to have occupied a narrow belt lying adjacent to platform facies on the east (Cobbing, 1985), but intervening facies relations are largely obscured by intrusion of the coastal batholith (Atherton and Webb, 1989) and tectonic juxtaposition of the two dissimilar facies tracts is an apparently feasible alternate interpretation. The Arequipa massif (Fig. 6), lying seaward from exposures of the volcanogenic assemblage (Shackleton et al., 1979), is composed of Proterozoic basement dissimilar in age to basement rocks of Amazonia forming the core of South America to the east of the Andes (Loewy et al., 2004). Although current interpretations posit incorporation of the “orphan” Arequipa (-Antofalla) block into the South American continent during Proterozoic time (Tosdal, 1996; Loewy et al., 2003, 2004), its position seaward from the volcanogenic Lower Cretaceous assemblage of oceanic aspect suggests accretion during Cretaceous time.

Interpretation of the thick volcanogenic assemblage of coastal Peru as the fill of a marginal basin has been strongly influenced by inferred analogy with the ophiolitic Rocas Verdes basin (Fig. 6) of southernmost South America (Atherton et al., 1983, 1985). The Rocas Verdes basin has been interpreted as a fossil marginal basin (Dalziel et al., 1974) that opened by Late Jurassic arc rifting (Bruhn et al., 1978) and closed by middle Cretaceous accordion tectonics (Dalziel, 1986) which evolved into retroarc thrusting (Fildani and Hessler, 2005). There are aspects of the Rocas Verdes history, however, that argue for an alternate interpretation as a remnant ocean basin that closed to accrete an exotic arc structure on the west to the southern tip of South America. No counterparts of the Middle to Upper Jurassic silicic volcanic suite so extensive east of the Rocas Verdes basin (Gust et al., 1985) can be identified with confidence among the Paleozoic wallrocks of the Cretaceous Patagonian batholith west of the Rocas Verdes basin (Hervé, 1988; Pankhurst et al., 1999), yet should be present there if the Rocas Verdes basin opened by Jurassic intra-arc rifting along the South American margin. Interpretation of the batholithic wallrocks as exotic to South America implies that Paleozoic basement (Hervé et al., 1988) of coastal Chilean ranges farther north is also exotic to South America. Structural relations and metamorphic gradients in the Paleozoic accretionary complex of coastal Chile document west-facing subduction (Martin et al., 1999), but given the proclivity of intraoceanic arcs to undergo episodic polarity reversal, the significance of that observation for Mesozoic tectonic relations is uncertain. In central Chile, the presence of twin Lower Cretaceous arc structures, one to the east and one to the west of the central valley (Ramos, 2000), suggests that the western arc in the coastal ranges west of the central valley was accreted to the continent along a Cretaceous suture now masked by sediment fill of the central valley.

Provisional reinterpretation of Mesozoic tectonic relations along the fringe of South America south of Ecuador thus suggests that a continuous belt (Fig. 6) of intraoceanic arc structures and associated exotic blocks has been accreted to South America by the diachronous closure of a remnant ocean basin that has been misinterpreted to date as a string of marginal seas occupying backarc basins. This alternate viewpoint challenges past interpretations of wholesale subduction erosion in the forearc of the Andes, and elsewhere in the Americas, because accretion of east-facing exotic arcs and of west-facing fringing arcs leads to quite different crustal architecture in the forearc region after accreted arcs are incorporated into the edge of a continental block (Fig. 7).

Forearc erosion

The two tectonic scenarios for arc accretion involving exotic arcs and fringing arcs produce different baselines for interpretations of the subsequent geologic evolution of a continental margin. For the case of "face-to face" arc-continent collision to accrete an intraoceanic island arc having a polarity opposed to that of the continental-margin arc (Fig. 7, uppermost panel), a post-collision forearc belt develops along the expanded continental margin, but pre-collision forearc belts are telescoped into the suture zone between arc and continent. For the case of "face-to-rear" arc-continent collision to accrete a fringing arc having the same polarity as the continental-margin arc, a pre-collision forearc belt is present along the expanded continental margin (Fig. 7, lowermost panel). Even where polarity reversal of the fringing arc precedes final accretion, an ancestral forearc belt is present along the expanded continental margin (Fig. 7, lower panels). Episodes of dormancy in the geologic history of the accreting arc structures lead to more complex scenarios for accretion (Fig. 7, middle panels), but do not alter the distinction between the post-accretion anatomy of the continental margin as expanded alternately by accretion of intraoceanic or fringing arcs.

Where accreted arcs are interpreted as fringing arcs of west-facing polarity, subduction erosion is commonly invoked to explain the absence of pre-accretion forearc belts along their Pacific flanks. If the accreted arcs were exotic intraoceanic arcs of east-facing polarity, this hypothesis is unnecessary because no pre-accretion forearc belts were ever present along their Pacific flanks representing the rear sides of the arc structures. To pursue this divergence in tectonic interpretation, consider episodes of forearc erosion proposed for Pacific margins of Alaska (Clift et al., 2005) and Peru-Chile (von Huene and Scholl, 1991).

Forearc belts of arc-trench systems are typically 75-125 km wide with crustal thicknesses of 15-25 km. In the Alaskan and Peru-Chile cases, removal within ~40 myr of forearc belts by subduction erosion would require reduction of forearc widths by ~2.5 km/myr and of forearc crustal profiles by ~50 km^2/myr. To achieve this rate of subduction erosion at typical trench subduction rates of 100 mm/yr (100 km/myr), subducted slabs must carry downward into the mantle a subducted blanket of eroded forearc crust averaging 500 m in thickness. Different assumptions of dimensions and rates would alter the inferred thickness of the tectonically eroded blanket of forearc crust capping the descending slab of lithosphere, but an appreciable thickness cannot be avoided if subduction erosion is a valid concept.

If this style of erosion of overriding crust were operative along intracontinental and intercontinental thrust belts, retrodeformation of thrust structures to recover pre-thrust stratigraphic configurations would be impossible. Yet palinspastic reconstruction of foreland thrust belts with full preservation of pre-thrust stratigraphy is a standard and generally successful technique for structural analysis. Unless one is prepared to suppose that rates of tectonic erosion at trenches exceed by orders of magnitude the rates of tectonic erosion that can be postulated for foreland thrust systems, past inferences of wholesale tectonic erosion along forearc belts may be logical artifacts stemming from the invalid interpretation of accreted intraoceanic arcs as fringing arcs.

For example, the southern flank of the Jurassic Talkeetna arc in southern Alaska can be viewed as the backarc of an accreted intraoceanic arc that had a polarity facing the continent (Dickinson, 2004). If so, no forearc belt coeval with Talkeetna arc activity would have been present except as deformed now within the Chulitna subduction complex (Fig. 6) north of the accreted arc, which reversed polarity after accretion, hence no subduction erosion is required to account for absence of a Jurassic forearc belt along the coastal southern flank of the accreted Talkeetna arc assemblage. Off Peru and Chile, the former presence of ancestral pre-Cretaceous forearc belts need not be inferred if the Pacific rim of South America is fringed by accreted intraoceanic arcs that collided with the continental margin after middle Cretaceous time (Fig. 6).

Acceptance of arc-continent collision as the means by which most accreted arcs were attached to the Cordilleran margins of the Americas is a more actualistic viewpoint than so-called accordion tectonics to collapse marginal seas. A shift in the guiding paradigm for arc accretion to the Americas from the accordion scenario to the collision scenario has multiple tectonic implications, but calling the concept of forearc tectonic erosion into question is perhaps the most far reaching. Supposed subduction erosion of forearc crust touches upon fundamental issues of crustal and mantle evolution (Scholl and von Huene, 2007) that are viewed differently if the volume of forearc crust transported into the mantle has been overstated. If forearc erosion is typically minimal, crustal volumes are more conserved over time during plate interactions and mantle is less contaminated with crustal materials through time.

LATERAL TERRANE TRANSPORT

Arc accretion to the margins of American continental blocks involved dominantly or exclusively longitudinal motions of accreted terranes to bring them against American coasts. Coastwise latitudinal motions of crustal entities termed tectonostratigraphic or lithotectonic terranes have also been inferred laterally along the North American continental margin based on paleomagnetic data (Hagstrum et al., 1985; Umhoefer, 1987; Beck, 1992; Irving et al., 1996). Although inferences of large-scale tectonic translation derived from paleomagnetic studies have been challenged (Butler et al., 1991, 2001a; Dickinson and Butler, 1998), they are still widely held (Housen et al., 2003; Symons et al., 2003; Enkin, 2006).

One technique for tracking relative motions of crustal blocks over time is to invert paleowander paths to recover paleomagnetic Euler poles (PEP), and thereby to determine absolute continental and terrane motions with respect to the geographic poles (Gordon et al., 1984). The method has limited utility for terrane analysis, however, because Euler poles at high latitudes result in short paleowander paths that are difficult to control or interpret. At the extreme, a paleowander path is a single point when the PEP pole for absolute plate motion coincides with the geographic pole, and terrane translation is entirely longitudinal.

Given the limitations of PEP analysis, paleomagnetic inclination discrepancies have been used as the principal means to gauge lateral terrane motions with respect to the interior of North America by assuming coastwise translation parallel to the Cordilleran continental margin. The rock masses for which inclination discrepancies have been measured and collated are dominantly clastic sedimentary strata and granitic plutons. In both instances, however, interpretation of observed paleomagnetic vectors in terms of paleolatitude is not straightforward.

Compaction shallowing

Reliance upon the observed inclinations of paleomagnetic vectors with respect to bedding in sedimentary strata as faithful records of initial depositional paleolatitude is unjustified because abundant datasets indicate that paleomagnetic vectors in sedimentary rocks are affected by compaction flattening which shallows the dip of the vectors. The typical effect is to introduce paleolatitude discrepancies of 5°-15°

TABLE 1. COMPACTION FLATTENING FACTORS FROM PALEOMAGNETIC STUDIES

Dataset	λ_o	λ_i	*f*	Reference
Paleocene of San Juan basin (NM)	~30°	37.5°	0.75	Kodama (1997)
Cretaceous Perforada Fm (Baja)	23.1°	28.2°	0.80	Vaughan et al. (2005)
Cretaceous Nanaimo Gp (BC)	31.5°	41.5°	0.70	Kim and Kodama (2004)
Cretaceous Nanaimo Gp (BC)	31.6°	42.0°	0.68	Krijgsman and Tauxe (2006)
Cretaceous Ladd Fm (CA)	27.3°	38.7°	0.65	Tan and Kodama (1998)
Cretaceous Pigeon Point Fm (CA)	21°	34°	0.57	Kodama and Ward (2001)
Cretaceous Point Loma Fm (CA)	21.2°	35.0°	0.55	Tan and Kodama (1998)
Triassic Newark Gp (NJ)	4° - 9°	8° -18°	0.45-0.65	Kent and Tauxe (2005)
Triassic Newark Gp (NJ)	~9°	~15°	~0.60	Tan et al. (2007)

Notes: λ=paleolatitude (λ_o=observed; λ_i=initial); $f = \tan I_o / \tan I_i$ (= $\tan \lambda_o / \tan \lambda_i$.) where I=inclination of paleomagnetic vector relative to bedding (I_o=observed; I_i=initial); geographic locations of datasets: Baja, Baja California; BC, British Columbia; CA, California; NJ, New Jersey; NM, New Mexico; stratigraphic abbreviations: Fm, Formation; Gp, Group.

(500-1500 km) without any terrane translation (Table 1). The magnitude of the effect can be gauged by the flattening factor (f), defined as a tangent function in the footnote to Table 1, which relates the observed inclination and implied original paleolatitude to the inferred initial inclination and actual original paleolatitude.

The paleolatitude discrepancies and flattening factors of Table 1 are not derived from geological arguments external to the paleomagnetic datasets, but are based upon internal treatment of the paleomagnetic data using either (a) elongation/inclination (E/I) analysis (Kent and Tauxe, 2005; Krijgsman and Tauxe, 2006) or (b) evaluation of the paleomagnetic anisotropy of magnetic susceptibility (AMS) or anhysteretic remanence (AAR), or both (Kodama, 1997; Tan and Kodama, 1998; Kodama and Ward, 2001; Kim and Kodama, 2004; Vaughan et al., 2005; Tan et al., 2007). Calculated flattening factors lie in the range of 0.45-0.80, with lower values indicative of greater inclination flattening. The near coincidence of flattening factors for the Nanaimo and Newark Groups (Table 1), as derived alternately from E/I and AMS-AAR analysis, gives confidence that both methodologies yield similar appraisals of compaction flattening. Flattening analysis involves no dismissal of any paleomagnetic data, but rather incorporates the full signal from paleomagnetic information into inferences of paleolatitude.

Because the flattening factor is a tangent function of inclination, paleolatitude discrepancies introduced by compaction flattening are highest at mid-latitudes. Flattening of the near-vertical inclinations acquired near the poles is analogous to pounding a steeply inclined stake into the ground, with minimal change in apparent paleolatitude, and squashing nearly flat inclinations acquired near the equator leaves inclinations still gently dipping. As shown by Figure 8, typical flattening factors of 0.50-0.75 result in paleolatitude discrepancies of <5° or <500 km near the equator or the poles, and this level of error is near the inherent uncertainty range (α_{95}) of paleopoles derived from paleomagnetic data.

At the latitudes of the USA and Canada, however, for which coastwise lateral motions of Cordilleran terranes have most commonly been inferred, flattening factors of 0.50-0.75 imply inherent discrepancies of 7.5°-17.5° or 750-1750 km between paleolatitudes derived from observed inclinations and inclinations adjusted for compaction flattening (Fig. 8). This range of potential paleolatitude discrepancies encompasses the general range of latitudinal transport suggested in the past for Cordilleran terranes, and suggests that many of the inferred northward motions of terranes are artifacts of a failure to correct observed inclinations for compaction flattening.

With the now well-documented effects of inclination flattening in mind, revision of segments of even continental paleowander paths that are controlled in large part by data from sedimentary rocks is currently underway (Tan et al., 2007). Given this wider perspective on paleomagnetic analysis, it is no longer permissible to use unadjusted paleomagnetic vectors from sedimentary rocks to infer initial paleolatitudes of deposition for displaced Cordilleran terranes. Flattening of inclination is not a panacea for all paleolatitude discrepancies (Kodama and Ward, 2001; Krijgsman and Tauxe, 2006), but flattening effects must be removed from paleomagnetic datasets before valid inferences of tectonic transport can be made. This exercise would reduce significantly the distances of coastwise translation inferred for Cordilleran terranes.

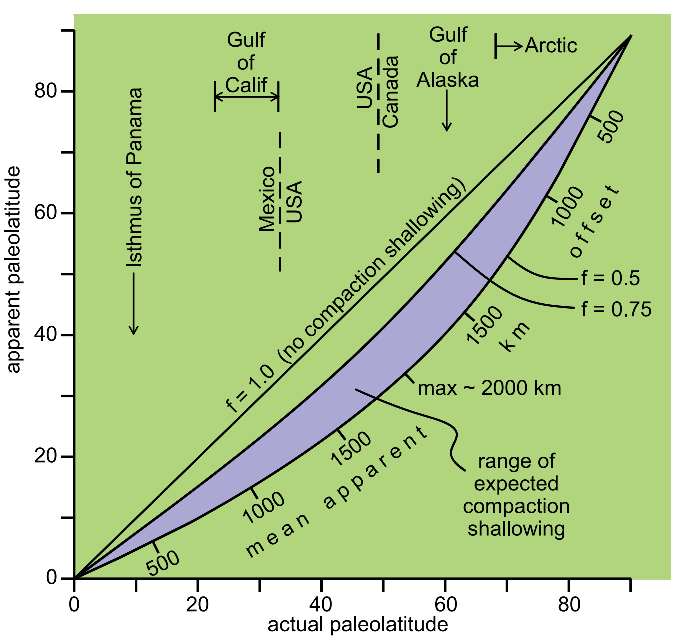

Figure 8. Apparent paleolatitude discrepancies derived from paleomagnetic data expected from documented range (Table 1) of compaction shallowing (flattening) of paleomagnetic vectors.

Pluton tilt

A second approach to gauging terrane motions has been to use palemagnetism recorded by granitic plutons assuming no deformation of the plutons since their emplacement. This assumption seems questionable in principle for rock bodies within an orogenic belt. Furthermore, there is a convincing argument based on the overall pattern of the pluton paleomagnetic data that the assumption is invalid. Apparent paleolatitude discrepancies for the plutons are better explained by tilt of the plutons than by transport of the plutons (Butzer et al., 2004; Butler et al., 2006).

Table 2 lists most of the Cordilleran plutons for which coastwise tectonic transport has been postulated on the basis of paleomagnetic data. If the paleomagnetic vectors recorded by the plutons are viewed as undisturbed since pluton emplacement, latitudinal displacement by 20°-40° or 2000-4000 km must be inferred. The paleomagnetic vectors record declination as well as inclination discrepancies, however, and both the inclination and declination discrepancies can be explained jointly by tilt of the plutons about axes subparallel to the strike of the Cordillera (Fig. 9).

TABLE 2. CORDILLERAN PALEOLATITUDE DISCREPANCIES (Δλ) FROM PLUTON TILT

Tilted Pluton	Δλ	Tilt	Control	Reference
Quottoon (BC)	20˚- 40˚	15˚- 40˚	multiple tiltblocks	Butler et al. (2001b)
Dundas Is. (BC)	20˚- 30˚	39˚	multiple tiltblocks	Butler et al. (2006)
Ecstall (BC)	5˚- 40˚	10˚- 70˚	internal deformation	Butler et al. (2002)
Captain Cove (BC)	30˚- 35˚	38˚	multiple tiltblocks	Butler et al. (2006)
McCauley Is. (BC)	20˚-30˚	37˚	multiple tiltblocks	Butler et al. (2006)
Spuzzum (BC)	20˚- 25˚	29˚	paleobarometry	Butler et al. (1989)
Mt. Stuart (WA)	25˚- 30˚	36˚	bedding in cover	Butler et al. (1990)
El Potrero (BaCa)	25˚- 30˚	47˚	paleobarometry	Cabello et al. (2006)

Note: locations of datasets: BaCa, Baja California (adjusted for Neogene San Andreas transform slip); BC, British Columbia; WA, Washington

For the hypothesis of pluton transport rather than pluton tilt to be valid, each pluton must have been transported thousands of kilometers laterally while maintaining paleohorizontality. Each must then have been uplifted by the amount necessary to expose deep-seated plutonic rock to erosion while still maintaining paleohorizontality. Finally, all the plutons must also have been twisted clockwise about vertical axes of tectonic rotation by the amounts required for declination discrepancies to mimic the effects of pluton tilt in place (Fig. 9). Data points for individual plutons are inherently ambiguous regarding the question of pluton transport and rotation versus pluton tilt because any tectonic scenario, no matter how complex, might be achieved once. To expect, however, that such rigorous constraints for tectonic transport, uplift, and rotation could be met repeatedly for multiple plutons along the trend of the Cordillera strains credulity. Pluton tilt thus emerges as the most parsimonious common denominator to explain the pluton paleomagnetic data and requires no appeal to latitudinal tectonic transport

The spurious effect of dismissing pluton tilt as an insig-

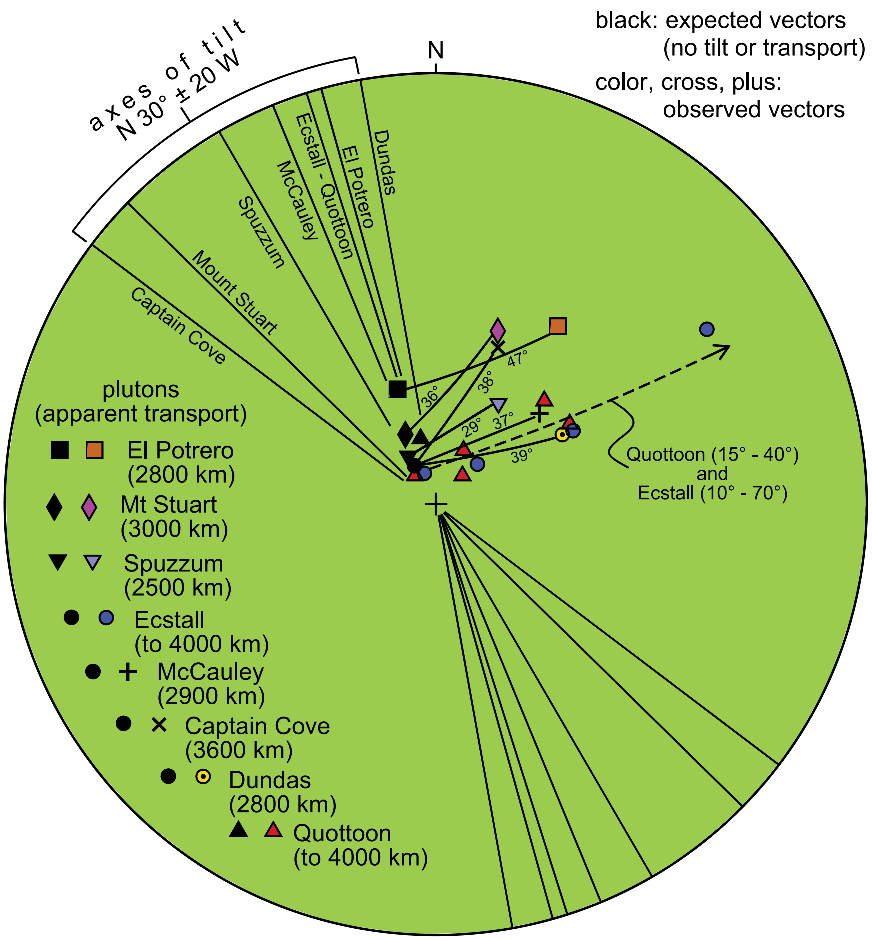

Figure 9. Discrepant paleomagnetic vectors from selected Cordilleran plutons (Table 2) interpreted alternately as reflecting post-emplacement tectonic transport by 2500-4000 km (lower left) or pluton tilt by 10°-70° in place (upper right) about axes indicated by NNW-SSE diagonal lines that are subparallel to the tectonic strike of the Cordillera.

nificant factor during Cordilleran evolution is shown by paleomagnetic data from different segments of the Peninsular Ranges batholith in California and Baja California. After restoration of paleomagnetic sites for Neogene San Andreas transform slip associated with opening of the Gulf of California, several untilted plutons in Baja California have yielded paleolatitude discrepancies that afford no evidence for excess tectonic transport: La Posta, 1°±6° (Symons et al., 2003); Los Cabos, 7°±8° (Schaaf et al., 2000); San Telmo, 3°±6° (Böhnel and Delgado-Argote, 2000). The El Testerazo pluton and San Marcos dike swarm yield a paleolatitude discrepancy of 7°±5°, but the apparent discrepancy is reduced to 1°±5° if the inclined dikes are restored to vertical (Böhnel et al., 2002). An apparent paleolatitude discrepancy of 11°±4° for plutons near the California border (Symons et al., 2003) is reduced to 3°±6° if paleobarometry is used to infer tilt of the batholith (Butler et al., 1991). Reliance on the discrepant paleomagnetic data from California unadjusted for pluton tilt, and thereby implying excess tectonic transport of Baja California, is not supported by any of the datasets from farther south on the Baja California peninsula (Ortega-Rivera, 2003). Hypotheses for tectonic transport of Baja California in excess of San Andreas slip are thus an artifact of ignoring pluton tilt.

Denying the possibility of coastwise lateral transport of plutons along the North American continental margin as parts of displaced blocks would be as faulty an assumption as denial of any pluton tilts. The data of Figure 9 may incorporate effects of both tectonic transport and pluton tilt in varying proportions from case to case. Paleomagnetic vectors from plutons should never be interpreted, however, as valid measures of initial paleolatitudes of pluton emplacement without independent structural or paleobarometric evidence adequate to constrain the planes of original horizontality within the plutons. The plot of Figure 9 implies that pluton tilt accounts for most discrepancies in both inclination and declination within Cordilleran plutons for which adequate paleomagnetic data are available, and suggests that coastwise tectonic transport of the plutons along the continental margin has been modest.

Paleomagnetic perspective

On balance, a marvelous paleomagnetic database for the North American Cordillera has been systematically underinterpreted by a persistent tendency to dismiss compaction flattening and pluton tilt as significant influences on the orientations of observed paleomagnetic vectors. As a result, tectonic interpretations based on invalid paleolatitudes derived from unadjusted paleomagnetic data have led to spurious syntheses from which there is no extrication short of conceptual retreat and wholesale reappraisal of the useful but misinterpreted paleomagnetic database.

SUMMARY CONCLUSIONS

The key insights drawn here from the global context, overall configuration, and internal anatomy of the circum-Pacific orogenic belt are the following: (a) major orogenic belts tend to follow great-circle paths on the globe, and this tendency can be exploited to aid reconstruction of ancient orogenic belts for which other constraints are inadequate to define their full courses; (b) the postulate of backarc basins along the western fringe of the Americas during Cordilleran evolution is a non-actualistic construct and most accreted arc structures were intraoceanic arcs attached to the Americas by arc-continent collision, which makes the concept of forearc subduction erosion an unnecessary postulate; (c) paleomagnetic vectors from sedimentary strata require adjustment for compaction flattening detected by E/I or AMS-AAR anisotropy analysis of paleomagnetic data, and paleomagnetic vectors from granitic plutons require adjustment for pluton tilt as controlled by structural or paleobarometric evidence, before valid paleolatitude estimates can be made from paleomagnetic observations.

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