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PALEOMAGNETISM AND MICROPLATE TECTONICS

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Introduction

This review briefly summarizes progress made over the last quadrennium (1987-1990) in the application of paleomagnetic methods to problems in microplate tectonics and structural geology, primarily within the orogenic belts of North America. These problems include delimiting the present configuration and past movements of microplates and displaced terranes near the continental margins, and the use of paleomagnetic vectors as structural markers to determine horizontal-axis (tilts) and vertical-axis rotations of crustal blocks associated with orogenic events. Contributions concerning apparent polar wander paths (APWPs) and the movements of larger scale plates are covered by *Geissman and Gordon* [this issue], and those concerning the application of magnetic studies to smaller scale tectonic fabrics and strain are covered by *Jackson and Tauxe* [this issue]. The rapid expansion of contributions to the field of paleomagnetism and microplate tectonics over the past two decades is evident from the narrowing in scope of this review and the preceding quadrennial report [*Hillhouse and McWilliams*, 1987]. Earlier reports [*Van der Voo*, 1979; *McWilliams*, 1983] included both paleomagnetic studies of cratonic rocks to determine reference APWPs and continental drift, as well as studies of rocks within orogenic belts to determine latitudinal displacements and/or azimuthal rotations of crustal blocks relative to their respective continental interiors. High-quality reference poles from cratonic rocks, however, remain of utmost importance to paleomagnetic interpretations of terrane displacements and block rotations [see *Van der Voo*, 1989].

The study of microplate tectonics along continental margins continues to be one of the more exciting and controversial aspects of paleomagnetic research. Since the early 1970s, paleomagnetic studies have supported stratigraphic and other geologic investigations in showing that distinct tectonostratigraphic terranes within the late Phanerozoic orogenic belt of western North America are allochthonous with respect to the stable craton. By the early 1980s, allochthonous terranes within the Paleozoic orogenic belts of eastern North America and Europe were beginning to be identified. In the western Cordillera, allochthonous terranes now have been found along the entire continental margin, and latitudinal displacements of these terranes up to several thousands of kilometers in magnitude have been determined [see *Beck*, 1989]. In addition to these displacements, systematic, regionally extensive block rotations are implied by the growing paleomagnetic data base [see *Beck*, 1988*a*]. Plate reconstruction models [*Engebretson et al.*, 1985, 1987; *Debiche et al.*, 1987; *Stock and Molnar*, 1988; *Cox et al.*, 1989] have provided a conceptual framework for analysis of terrane displacements along the ancient western margin of North America by showing large northward components of relative motion during right-oblique convergence since mid-Cretaceous time. Prior to this, terranes may have moved southward along the margin during left-oblique convergence since Triassic time [*Ave Lallemant and Oldow*, 1988; *May et al.*, 1989]. Furthermore, geophysical and geological studies of modern subduction zones [e.g. *Jarrard*, 1986*a*, 1986*b*] have provided a mechanism for coastwise displacements by showing that movement of forearc slivers is a likely consequence of oblique subduction and concomitant arc parallel strike-slip faulting. Large estimates of northward displacement (>1000 km), however, conflict with more conservative reconstructions of the western North American margin based primarily on restoration of Neogene strike-slip faulting [see *Butler et al.*, in press]. In order to reconcile this conflict between interpretations of the geologic and paleomagnetic data sets, alternative explanations of the paleomagnetic data recently have been proposed. These explanations include revisions of the reference APWP [*May and Butler*, 1986], regional tilting of batholithic rocks [*Butler et al.*, 1989], and possible compaction error for sedimentary rocks [*Butler et al.*, in press].

In the northern Appalachian orogen, conflicting data concerning the sense, age, and location of Late Paleozoic terrane displacements apparently have been resolved with the recognition that Late Devonian and early Carboniferous reference poles from the craton were actually based on regional Late Paleozoic remagnetizations [see *Van der Voo*, 1989]. These widespread remagnetizations have been related to low-temperature alteration associated with migration of orogenic fluids from the continental margin towards the continental interior during Alleghanian thrusting [*Oliver*, 1986], and have important implications for paleomagnetic studies in other orogenic belts [*McCabe and Elmore*, 1989; *Elmore and McCabe*, this issue].

A significant amount of new paleomagnetic data from orogenic belts around the world has been published over the past four years. We have attempted to make the bibliography of this review as comprehensive as possible, although our focus has been on contributions made by U.S. authors, and, due to page restrictions, primarily on those reports concerning tectonic and structural studies in the western Cordillera and Appalachian orogen of North America. Due to increasing interest in the region, we have also included a smaller section on tectonic studies in South America.

Western Cordillera of North America

Alaska

The last decade has brought significant advances in the comprehension of the structure, geology, and accretionary tectonics of southern Alaska and the northern Pacific Basin [*Coney*, 1987, 1989; *Howell and Jones*, 1989; *Howell*, 1989; *Wallace et al.*, 1989]. Present analysis of the geologic framework of this region is strongly based on the concept of tectonostratigraphic terranes [*Coney*, 1989; *Howell and Jones*, 1989; *Stavsky et al.*, 1990], and southern Alaska is interpreted to consist of the Prince William, Chugach, Peninsular, and Wrangellia terranes [*Howell and Jones*, 1989; *Howell*, 1989; *Nokleberg et al.*, 1989]. During the last quadrennium, paleomagnetic research in southern Alaska has continued to focus

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on more precisely determining the boundaries and accretion times of major terranes within the southern Alaska terrane itself, and on block deformation associated with formation of the Alaskan orocline. In addition, paleomagnetism has been applied to determine whether crust beneath the Yukon-Koyukuk basin represents an accreted terrane which has experienced significant post-Early Cretaceous northward translation with respect to North America, and to determine the deformation of tectonic blocks in the northern Alaskan region associated with rotational opening of the Canada Basin.

The available results from more than fifty paleomagnetic studies show poleward motion of the Wrangellia, Peninsular, Chugach, and Prince William terranes during Mesozoic and early Cenozoic time with respect to the North American plate [*Coe et al.*, 1985; *Thrupp and Coe*, 1986; *Hillhouse*, 1987; *Hillhouse and McWilliams*, 1987; *Stone and McWilliams*, 1989; *Panuska et al.*, 1990]; reliability criteria proposed by many workers are useful in reviewing this data set [*Coe et al.*, 1985; *Hillhouse*, 1987; *Van der Voo*, 1988; *Harbert*, in press]. Despite numerous studies, there is a still a fundamental disagreement between paleolatitudes for the Peninsular terrane derived from lower Tertiary volcanic rocks north of the Castle Mountain fault, which indicate no relative motion between North America and this region [e.g. *Hillhouse et al.*, 1985], and coeval sedimentary and complexly deformed units south of this fault, which indicate significant northward displacement [e.g. *Stamatakos et al.*, 1989]. Differential lateral movements of crustal blocks, sedimentary inclination error, and insufficient age control all have been proposed to explain this discrepancy in paleolatitudes [*Hillhouse and McWilliams*, 1987; *Stamatakos et al.*, 1989; *Panuska et al.*, 1990].

Bol and Coe [1987] sampled units on Resurrection Peninsula in southern Alaska consisting of sheeted dikes, basalt flows and pillow basalts. Their results show $13^\circ \pm 6^\circ$ of northward transport of these rocks with respect to North America since early Tertiary time. *Stamatakos et al.* [1989] collected paleomagnetic samples from Late Cretaceous rocks of the Matanuska Formation north of the Castle Mountain fault. Only four sites exhibited stable magnetizations, but their site-mean directions were more closely grouped in stratigraphic than geographic coordinates indicating a prefolding age for the magnetization. The overall mean pole for these four sites indicate 2880 ± 2000 km of poleward displacement when compared with the Late Cretaceous reference pole for North America. Paleomagnetic data for samples collected from the Paleocene Chickaloon and Arkose Ridge Formations show 1600 ± 1200 km of poleward motion, but indicate no latitudinal offset across the Castle Mountain fault since deposition. In addition, the data for the Chickaloon Formation show clockwise rotation in declination, whereas the data for the Arkose Ridge and Mantanuska Formations indicate counterclockwise rotation in declination with respect to the North American APWP. The paleomagnetic data for Eocene sills in the Matanuska Valley indicate no northward relative motion since 40 Ma, and also show about 50° of clockwise rotation relative to North America [*Stamatakos et al.*, 1988]. This result also agrees with that of *Thrupp and Coe* [1986], who, using thermal demagnetization to investigate well-bedded Paleogene volcanic flows of the Peninsular terrane, showed no significant relative latitudinal motion of these units with respect to the North American plate.

On the basis of stratigraphic onlap relations between terranes, estimates of the age of suturing of the Peninsular, Wrangellia, and Alexander terranes to each other, but not necessarily to North America, are between 140 and 150 Ma [*Wallace et al.*, 1989]. Contact relations between Carboniferous plutons, however, appear to suggest no separation of these terranes after 300 Ma [*Plafker et al.*, 1989]. Additional deformation at approximately 115 Ma has been interpreted as recording the first contact of this amalgamation of terranes with the North American plate [*Nokleberg et al.*, 1989], and may have occurred at some distance to the south along the North American margin [*Wallace et al.*, 1989; *Nokleberg et al.*, 1989]. Estimates of the accretion time for this large terrane with North America are between 98 and 66 Ma based on intense deformation in the Kahiltna Flysch basin that bounds the Peninsular terrane along its northwest margin [*Nokleberg et al.*, 1989; *Wallace et al.*, 1989], or in the late Paleocene to late Tertiary based on paleomagnetic arguments [*Stamatakos et al.*, 1988, 1989; *Panuska et al.*, 1990].

Recent geological studies of the Alexander terrane [*Gehrels and Saleeby*, 1987; *Gehrels et al.*, 1987; *Stowell and Hooper*, 1990], the Border Ranges fault [*Little*, 1990; *Little and Naeser*, 1989], and deformation of the Kodiak Formation [*Paterson and Sample*, 1988; *Sample and Moore*, 1987] indicate significant Late Cretaceous to early Tertiary deformation which may be related to terrane motion along the eastern margin of the Pacific Basin. *Coe et al.* [1989] present a summary of latest Cretaceous and early Tertiary paleomagnetic data from southern Alaska showing consistent counterclockwise rotation of magnetic declinations ($44^\circ \pm 11^\circ$), which they interpret to record deformation of the entire Alaskan peninsula in a fashion akin to kink folding about a vertical axis. This "megakinking" is inferred to have formed in response to Eurasian and North American relative plate motion [*Coe et al.*, 1989]. Interaction of the Eurasian and North American plates in the Alaskan region as the North Atlantic ocean opened also has been described by *Harbert et al.* [1987] and *Rowley and Lottes* [1988]. *Plumley et al.* [1989] studied Paleozoic carbonate rocks in northeastern Alaska and inferred that these rocks were overprinted in early to middle Tertiary time. Discordance of the paleomagnetic directions in declination only imply that these rocks have been rotated clockwise 45° to 90° producing the eastern Brooks Range orocline.

The Yukon-Koyukuk basin of west-central Alaska has come under investigation as a suspect terrane, as it is bounded by structurally complex units, some containing ophiolites, such as the Seward, Ruby, and Arctic Alaska terranes [*Patton and Box*, 1989]. Paleomagnetic results from Cretaceous units [*Hillhouse and Gromme*, 1988; *Harris et al.*, 1987] indicate significant latitudinal translations in the Yukon-Koyukuk province. *Harris et al.* [1987] report a 15° paleolatitude anomaly and suggest this poleward motion occurred after 97 Ma. *Hillhouse and Gromme* [1988], while showing that 1500 ± 800 km of poleward motion has occurred, suggest that this motion could have been completed by the end of Early Cretaceous time, consistent with the continuity of Late Cretaceous units in this region. *Halgedahl and Jarrard* [1987] reported results from the Arctic Alaska terrane which indicate large-scale counterclockwise rotation of the Brooks Range, but no significant displacement in terms of paleolatitude. This is a key result in that it strongly supports a rotational opening of the Canada Basin [*Scotese et al.*, 1988; *Wilson et al.*, 1989; *Stone*, 1989; *Harbert et al.*, 1990], but is in apparent disparity with the results of *Harris et al.* [1987].

In the Aleutian Islands, new paleomagnetic data from early Oligocene rocks show significant clockwise rotation but little latitudinal displacement when compared to North America [*Harbert*, 1987]. This result is in agreement with other new paleomagnetic data from Upper Cretaceous units of St. Matthew Island in the Bering Sea [*Wittbrodt et al.*, 1989]. Deformation and clockwise block rotation along the Aleutian arc massif also have been observed using reflection seismic methods [*Geist et al.*, 1988; *Ryan and Scholl*, 1989] and are consistent with the paleomagnetic results.

Pacific Northwest

One of the more controvertial issues to emerge over the last four years has been the paleogeographic origins of the Coast Plutonic Complex of British Columbia. Paleomagnetic directions for middle Cretaceous rocks of the Coast Plutonic Complex are discordant with reference directions from Cretaceous rocks of the North American craton and indicate over 2000 km of northward displacement and about 60° of clockwise rotation relative to North America [*Irving et al.*, 1985]. Petrologic data, however, imply that the Complex has been tilted about 30° to the SW which also could account for the discordant paleomagnetic data [*Butler et al.*, 1989]. *Irving et al.* [1985] considered the translation and rotation option more likely because systematic tilts over such a large region seemed improbable. Furthermore, this tectonic displacement of British Columbia is consistent with other paleomagnetic data from southern Alaska, northern Washington, and the Yukon, and displacement models for this allochthonous block (Baja British Columbia) outboard of the Tintina-Northern Rocky Mountain Trench fault, based on reconstructed plate kinematics of the Pacific Basin, have been proposed by *Umhoefer* [1987] and *Umhoefer et al.* [1989]. In addition, a reliable paleopole for the well-bedded Upper Cretaceous volcanic rocks of the Carmacks Group in nothern British Columbia [*Marquis and Globerman*, 1988], indicates 1500 km of northward translation relative to the craton. This result supports displacement of the Coast Plutonic Complex, but has been challenged by *Butler* [1990] on the grounds that the minimum displacement required by the 95% confidence limits is as small as 100 km. *Marquis et al.* [1990] point out, however, that errors in displacement may be assumed to be normally distributed, with the maximum likelihood value being 1500 km. Thus, based on these data, a displacement less than 500 km is just as likely as one of more than 2000 km. *Irving and Thorkelson* [1990] have recently reported paleomagnetic results from the bedded mid-Cretaceous Spences Bridge Group in southwestern British Columbia which indicate 1725 ± 790 km of northward displacement and 66° ± 12° of clockwise rotation relative to North America. These data, in conjuction with other Cretaceous data for the Pacific Northwest, support the translation hypothesis, and show an increase in apparent northward displacement from east to west across the Cordillera.

Northward displacements (though smaller) and vertical-axis rotations are also implied by data acquired from the Lower Jurassic Bonanza Group of Vancouver Island [*Irving and Yole*, 1987] and the Sylvester Allochthon of north-central British Columbia [*Butler et al.*, 1988]. Paleomagnetic data for the Eocene Kamloops Group [*Symons and Wellings*, 1989], Marron volcanics [*Bardoux and Irving*, 1989], Flores volcanics [*Irving and Brandon*, 1990], and Ootsa Lake Group [*Vandall and Palmer*, 1990] of British Columbia all indicate that displacements in the region were completed by early to middle Eocene time.

In the Cascade arc and adjacent areas, paleomagnetic results from Cenozoic (62-12 Ma) volcanic and sedimentary rocks indicate that moderate to large (15°-80°) clockwise rotations have occurred throughout the region [*Wells and Heller*, 1988]. *Wells et al.* [1989], using paleomagnetic directions for paleomagnetically and chemically correlated flows of the Columbia River Basalt Group, show 16° to 30° of clockwise rotation of the coast with respect to the Columbia River Plateau since middle Miocene time. Apparent increases of rotation with age and proximity to the coast imply that the rotations were caused by distributed dextral shear driven by the oblique subduction of oceanic plates to the west during Cenozoic time [*Wells*, 1989]. An average southward increase in the continental margin rotations into the region outboard of the Basin and Range province indicates that intra-arc or backarc extension also made a significant contribution to the magnitude of the observed rotations [*Wells*, 1990]. *Mankinen et al.* [1987], however, compared coeval lava flows of the High Lava Plains of south-central Oregon with those of the Columbia River Basalt Group of southeastern Washington, using the magnetic-polarity reversal observed within the Steens Basalt as a stratigraphic marker (15.5 Ma), and showed that neither differential rotation between these two regions nor absolute rotation of them has occurred since about 20 Ma.

A synfolding magnetization for the Late Cretaceous Winthrop Sandstone and the Cretaceous Midnight Peak Formation in the Methow-Pasayten belt of north-central Washington implies clockwise rotation (48°) as well as poleward transport of these rocks about 1400 km between Late Cretaceous and Eocene time [*Granirer et al.*, 1986]. A more recent study [*Bazard et al.*, 1990], however, indicates that rocks in this region were partly to completely remagnetized at different times during folding, and that a clear estimate of paleohorizontal cannot be made. Paleomagnetic data for the Upper Jurassic James Island Formation in the Decatur terrane, located in the San Juan Islands of northwestern Washington, show positive fold and reversal tests implying that the magnetization is primary [*Bogue et al.*, 1989]. Thus, deposition at equatorial paleolatitudes and subsequent large-scale northward transport of the Decatur terrane as part of a larger tectonic element, including the Coast Plutonic Complex of British Columbia, are indicated by the paleomagnetic inclinations for the James Island Formation [*Bogue et al.*, 1989].

Northern California

Declination anomalies for Permian and Triassic volcanic and sedimentary strata of the Eastern Klamath terrane, northern California, show clockwise rotations of ~100°, while those for Jurassic strata and plutons indicate clockwise rotations of ~60°, implying a progressive rotation of the Klamath Mountains province between latest Triassic or earliest Jurassic time, and accretion of the Klamath Mountains terranes to the North American continent by Early to mid-Cretaceous time [*Mankinen et al.*, 1989]. Limited data from a complexly deformed part of the Permian Nosoni Formation in the Eastern Klamath terrane [*Renne et al.*, 1988], however, seem to show no discordance relative to cratonic North America. Paleomagnetic data for the Shasta Bally belt of Cretaceous plutons in the Klamath Mountains indicate that these rocks have been rotated ~25° clockwise relative to North America since Early Cretaceous time [*Mankinen et al.*, 1988]. Overall, the paleomagnetic data for the Klamath Mountains terranes show no evidence of significant latitudinal displacement with respect to North America, consistent with the general trend of data for the Sierra Nevada and Blue Mountains regions as well [*Mankinen and Irwin*, in press]. Within the central Sierra Nevada, *Ross* [1988] used paleomagnetic methods to study a sigmoidal pattern of kink folding. Divergent declinations indicate that only part of the folding could have occurred after cooling below magnetic blocking temperatures.

A new study of the accreted blocks of the Laytonville Limestone [*Tarduno et al.*, 1990] in the Franciscan Complex of northern California has corroborated previous interpretations [*Alvarez et al.*, 1980; *Tarduno et al.*, 1986] that the limestones were initially deposited and magnetized in the southern hemisphere, and that northward transport towards the equator during deposition is marked by an apparent decrease in inclination with time. The remanent magnetization can be shown to predate breakup and deformation of the limestone blocks within the subduction complex, and the observed uniformly normal-polarity magnetizations would be expected because the limestone was deposited during the Cretaceous Normal-Polarity Superchron. Deposition of the limestone in the southern hemisphere, however, would require exceptional plate velocities to satisfy geologic evidence that these rocks were accreted in the northern hemisphere by early Tertiary time.

Recently, however, *Hagstrum* [1990] has suggested that the accreted fragments of oceanic crust incorporated within the Franciscan Complex were remagnetized while still part of the subducting slab beneath an ancient accretionary prism. Remagnetization prior to structural deformation would explain why almost all of these rocks have only single-polarity magnetizations, especially those deposited during mixed-polarity intervals of the geomagnetic field (e.g. Marin Headlands terrane, Nicasio Reservoir terrane). Thus, negative inclinations for the Laytonville Limestone are more simply explained by its remagnetization in the northern hemisphere in a reversed-polarity field. Shallow-dip angles are inferred for the accreted rocks of the Franciscan Complex at the time of remagnetization based on the configuration of modern subduction zones [*Karig*, 1980], and structurally-corrected magnetizations consistently indicate northward coastwise displacements and clockwise rotations relative to North America since accretion of these rocks during Late Cretaceous and early Tertiary time [*Hagstrum*, 1990]. Remagnetization of the Coast Range ophiolite and the overlying Great Valley sequence and Days Creek Formation is also indicated by data from sites in northern California and southwest Oregon [*Frei and Blake*, 1987]. Comparison of the *in situ* paleomagnetic directions with reference directions for North America imply that remagnetization occurred between Late Cretaceous and Holocene time, perhaps as a result of burial and uplift, although low-temperature chemical remagnetization remains a possibility.

Paleomagnetic study of the Butano Sandstone, recovered as azimuthally unoriented cores from exploratory oil wells in the Santa Cruz Mountains, was undertaken to determine the Eocene paleolatitude of the Salinia terrane [*Kanter*, 1988]. The Salinia terrane is an allochthonous fragment of granitic crust which lies west of the San Andreas fault. Previous paleomagnetic work in Upper Cretaceous and Paleocene turbidites [*Champion et al.*, 1984] indicates that Salinia has been tranported northward 2500 km since Cretaceous time, although possible geologic correlations of Salinian granites with apparently similar rocks in the southern Sierra Nevada and Peninsular Ranges batholiths imply that movement of the Salinia terrane may have been much less [e.g. *Ross*, 1984]. The mean paleolatitude for the Butano Sandstone supports the correlation of these rocks with the Point of Rocks Sandstone Member (of the Kreyenhagen Formation) to the south implying that the Salinia terrane has been moved northward only the 315 km associated with Neogene displacement on the San Andreas fault system since early to middle Eocene time [*Kanter*, 1988].

Southern California and Mexico

Recent paleomagnetic studies of Late Cretaceous sedimentary rocks within the Peninsular Ranges terrane of northwestern Mexico and southwestern California [*Filmer and Kirschvink*, 1989; *Bannon et al.*, 1989] have corroborated previous studies and contributed to a growing body of data which consistently indicates that the Peninsular Ranges terrane was translated northward approximately 8° in latitude (900 km) and rotated 27° clockwise since Late Cretaceous time [see *Lund and Bottjer*, in press; *Hagstrum and Filmer*, in press]. *Butler et al.* [in press], however, suggest that a uniform SW tilt of the Peninsular Ranges batholith and compaction shallowing of paleomagnetic inclinations in the overlying sedimentary rocks could also explain the discordant Cretaceous paleopoles for the Peninsular Ranges terrane. This explanation, similar to one advanced for the Coast Plutonic Complex of British Columbia [*Butler et al.*, 1989], requires that widespread tilting of plutonic rocks and compaction shallowing in sedimentary rocks resulted in surprisingly consistent amounts of paleolatitudinal discordance. In contrast, *Hagstrum et al.* [1985] cited this consistency in support of arguments involving northward translation.

Magnetization directions measured by *Bannon et al.* [1989] in samples from the Campanian to Maestrichtian Point Loma Formation pass both reversal and fold tests, and fossil occurrences indicate that the reversed magnetozone correlates with Chron 32r. Paleomagnetic and rock magnetic investigations by *Filmer and Kirschvink* [1989] on samples from the coeval Rosario Formation along the western coast of Baja California show highly stable normal and reversed polarity components in rocks which, on the basis of biochemical investigations of ammonite fossils [*Weiner and Lowenstam*, 1980], have not been chemically or thermally altered since deposition. Biostratigraphic and paleomagnetic study of early Eocene strata from Baja California near Rosarito [*Flynn et al.*, 1989], however, imply that the Peninsular Ranges terrane was part of North America by Chron 23r. This result is consistent with a geochemical correlation between clasts from conglomerates of the Eocene Poway Group in the Peninsular Ranges terrane and source rocks in northwestern Sonora [*Abbott and Smith*, 1989]. Estimates of potential coastwise displacement of the Peninsular Ranges terrane, based on models of oblique subduction and arc parallel strike-slip faulting, imply that a 900-km-northward displacement could have been accomplished between Chrons 32r and 23r ($\simeq$70 to $\simeq$50 Ma) by either the Farallon or Kula plate (or both) depending on the trend of the North American margin and efficiency of the mechanism of transport [*Hagstrum and Filmer*, in press].

Large-scale northward transport (2800 km) and clockwise rotation (56°) of the Western Baja terrane was also inferred from paleomagnetic data for sections of Late Triassic to Early Cretaceous radiolarian chert [*Hagstrum and Sedlock*, 1990]. Although uniform polarity directions throughout the sections indicate remagnetization, the data pass a tilt test implying that remagnetization predated deformation and underplating from the subducting slab, and therefore probably occurred at shallow-dip angles beneath the accretionary prism [see *Karig*, 1980]. Paleomagnetic results for the Oaxaca and Acatlan terranes of southern Mexico also indicate that these rocks have been displaced relative to North America. Rocks equivalent in age to those of the Grenville Complex occurring in the Oaxaca terrane have a steep-inclination characteristic magnetization indicating that this terrane was at much higher latitudes during Grenvillian time [*Ballard et al.*, 1989]. Late Paleozoic to early Mesozoic remagnetizations of Paleozoic rocks in the Oaxaca and Acatlan terranes, however, do not indicate latitudinal displacements, but imply subsequent counterclockwise and clockwise rotations, respectively [*McCabe et al.*, 1988; *Fang et al.*, 1989].

Further studies of Neogene rocks in southern California in the western and eastern Transverse Ranges [*Hornafius et al.*, 1986; *Carter et al.*, 1987] and in the western Mojave desert [*Golombek and Brown*, 1988] showed clockwise vertical-axis rotations. In combination with geometric models, these rotations have been used to calculate the amount of strike-slip displacement on the major faults of the region [*Luyendyk and Hornafius*, 1987; *Luyendyk*, 1989]. A large early Miocene clockwise rotation (50°) of volcanic rocks in the central Mojave desert was reported by *Ross et al.* [1989], but smaller clockwise rotations of the early to middle Miocene Hector Formation (20°) and of the middle and late Miocene Barstow Formation (possibly 4°) indicate a more complex structural history of the region where individual blocks have undergone different amounts of rotational deformation [*MacFadden et al.*, 1990*a*, 1990*b*]. More detailed magnetostratigraphic studies have been used to determine temporally constrained tectonic rotations and the timing of slip on the San Andreas fault [*Chang et al.*, 1987] and on the Garlock fault [*Burbank and Whistler*, 1987]. *Verosub and Holm* [1989] also applied magnetostratigraphic techniques to tectonic rotation studies of Miocene and Pliocene sediments in California. New evidence indicates that Ridge Basin, southern California, rotated about 20° clockwise prior to 7.5 Ma, and that the Purisima Formation of the Pigeon Point block, central California, has been rotated 50° clockwise since 3.4 Ma.

Basin and Range and Rocky Mountain Provinces

A new paleomagnetic study of the Peach Springs Tuff (19 Ma) by *Wells and Hillhouse* [1989] has confirmed the correlation of this unit at 41 localities across the southern Basin and Range province from the Colorado Plateau to the central Mojave desert. Comparisons of the individual site-mean directions with a Plateau reference direction indicate generally consistent directions across the region with the exceptions of small (<13°) patternless rotations in the Mojave desert, and large (37°-51°) clockwise and counterclockwise rotations in the Colorado River extensional corridor. Paleomagnetic data for Miocene volcanic rocks from across the Mojave-Sonora desert region of southeastern California and western Arizona [*Schweig*, 1989; *Calderone et al.*, 1990], and from the Baja California peninsula [*Hagstrum et al.*, 1987], also indicate no significant translations or systematic rotations within the region since Miocene time. In southern Nevada, clockwise rotations (50°-70°) and oroflexural bending of the Las Vegas Range associated with the Las Vegas Valley Shear Zone (<17 Ma) was documented by *Nelson and Jones* [1987]. The paleomagnetic data indicate that the bending of the Las Vegas Range was accomplished by the rotation of smaller blocks modelled as responding to continuous deformation at depth. Clockwise rotation (30°) of Miocene ash-flow tuffs (<13 Ma) was also observed at the southern end of Yucca Mountain [*Rosenbaum et al.*, in press], and earlier clockwise rotations were documented for the Silver Bell Mountains (40°) in south-central Arizona in Late Cretaceous to early Tertiary time [*Hagstrum and Sawyer*, 1989].

Clockwise rotation of the Colorado Plateau has been proposed based on geologic arguments to have occurred mostly during Laramide compression, but also partly during late Cenozoic extension associated with opening of the Rio Grande rift [*Hamilton*, 1988]. Differences between paleomagnetic poles from the Plateau and from the stable craton support these arguments, but different estimates of the magnitude of the rotation have been presented. *Steiner* [1986, 1988] directly compared Paleozoic and Mesozoic poles and concluded that the Plateau has been rotated $11^\circ \pm 4^\circ$ clockwise relative to the craton. As noted by *Hillhouse and McWilliams* [1987] and *Van der Voo* [1989], near coincidence of the rotated poles with the reference APWP could cause errors in the pole ages to influence estimates of rotation. *Bryan and Gordon* [1986, 1990], therefore, compared the systematic difference between all poles on and off the Plateau and estimate the rotation to be $5.0^\circ \pm 2.4^\circ$ clockwise.

Contributions of block rotation and associated strike-slip faulting to middle Cenozoic extension also have been the focus of recent paleomagnetic studies in the Basin and Range province. *Hudson and Geissman* [1987, 1988] determined a 25° counterclockwise rotation in Oligocene to early Miocene ash-flow tuffs in the northern Dixie Valley region of west-central Nevada. The rotation accompanied the ash-flow volcanism and was apparently associated with right-lateral slip on NW-trending faults. *Li et al.* [1990] also determined counterclockwise rotations (~19°) of middle Miocene units in the north Nevada rift possibly related to right-lateral movement on NW-trending oblique-slip faults. In east-central Nevada, *Hagstrum and Gans* [1989] used paleomagnetic data from the widespread Kalamazoo Tuff (35 Ma) to show a relative rotation of 28° between the N-S margins of a zone of highly-extended crust. A more complex pattern of rotated and unrotated domains has been shown by a paleomagnetic study of middle Eocene rocks of the Challis volcanics in east-central Idaho. *Janecke et al.* [in press] explain this pattern by differential rotation of the hanging wall of a major low-angle fault associated with the opening of a half-graben during Eocene to Oligocene time.

Skalbeck et al. [1989] report paleomagnetic directions for the Late Permian to Early Triassic Koipato Volcanics in west-central Nevada which are discordant with respect to the North American APWP. Positive fold and reversal tests imply that the characteristic magnetization is primary and that it indicates 1400 km of southward transport and 25° of clockwise rotation. These data have important implications for the paleogeographic origins of the Golconda allochthon which was displaced at least 80 km eastward across the western edge of North America during the Sonoma orogeny. *Geissman et al.* [1990], however, found Middle Triassic limestones of the Prida Formation, overlying the Koipato Volcanics, to have been remagnetized in latest Middle to Late Jurassic time. A pervasive remagnetization, therefore, might explain the discordant directions in the volcanic rocks as well.

Paleomagnetic studies in the overthrust belt of the northern Rocky Mountains continue to show large vertical-axis rotations as well as synfolding remagnetization within the thrust sheets. New work in the Helena salient of Montana indicates that the thrust sheets broke into individual pieces during deformation [*Eldredge and Van der Voo*, 1988], and paleomagnetic and isotopic age data imply that deformation occurred during middle to late Paleocene time [*Harlan et al.*, 1988]. In addition, syndeformational remagnetizations in the Wyoming-Idaho-Utah thrust belt were documented in the Jurassic Preuss Sandstone [*Hudson et al.*, 1989] and in the Jurassic Twin Creek Limestone of the Prospect Thrust [*McWhinnie et al.*, 1990].

Paleomagnetic methods were also used to estimate tilts (horizontal-axis rotations) in order to determine the displacement history on latest Quaternary normal faults in Idaho and Wyoming associated with the eastward migration of the Yellowstone hotspot [*Anders et al.*, 1989], to determine the tilts of crystalline basement rocks involved in the development of a major extensional accomodation zone in northwestern Arizona and southern Nevada [*Faulds et al.*, in press], and to determine the structural history of mineralized plutonic rocks in the Ajo mining district of southern Arizona [*Hagstrum et al.*, 1987].

Appalachian Orogen

Paleomagnetic investigations in eastern North America have continued to concentrate on the delineation of terrane boundaries and clarification of displacement histories for allochthonous terranes [e.g. *Van der Voo*, 1988*a*, 1989; *Briden et al.*, 1988; *Kent and Keppie*, 1988], on the definition of zones of declination anomalies related to oroclinal bending [e.g. *Kent*, 1988], on the description of the Proterozoic, Paleozoic and early Mesozoic segments of the APWP for North America which bear heavily on interpretations of terrane displacements and rotations [e.g. *Kent and May*, 1987; *Van der Voo*, 1988*b*, 1990; *Kent and Van der Voo*, 1990], and on a more complete understanding of the nature of secondary magnetizations observed in Appalachian rocks and their implications for, and relations to, orogenic events [e.g. *Bachtadse et al.*, 1987; *Sterns and Van der Voo*, 1987; *Miller and Kent*, 1988*a*; *Jackson et al.*, 1988; *Tucker and Kent*, 1988; *Elmore and McCabe*, this issue].

Similar to those paleomagnetic data from the western Cordillera previously discussed, data from the Appalachian region of eastern North America strongly support a model in which the Appalachian orogen consists of a collage of accreted Paleozoic terranes. Repetitive cycles of seafloor spreading and plate collision (Wilson cycles) have caused complex reactivation of terrane-bounding faults and polyphase deformation, thus complicating paleomagnetic studies in this region. The Avalon basement of eastern Newfoundland is the type area for a set of terranes, with distinct geologic similarities, which are found along the Canadian Maritime coast in Nova Scotia and New Brunswick, in the Boston Basin, in the southern Appalachian Piedmont, and in northern Florida [*Van der Voo*, 1988*a*]. Due to the recognition that Late Devonian and early Carboniferous poles for North America were based on late Paleozoic remagnetizations [see *Kent and May*, 1987], there is presently no support for major displacements between "Acadia" and North America since Late Devonian time. Major displacements between the Avalon terranes and the North American craton, however, appear to have occurred prior to docking of these terranes during or preceding the collision of Gondwana with North America which caused the Acadian orogeny [*Van der Voo*, 1989].

A number of new paleomagnetic studies completed during this past quadrennium have focused on constraining Paleozoic paleolatitudes for the Avalon basement terrane in the Canadian Maritime region. Paleomagnetic study of the Late Ordovician to Early Silurian Dunn Point volcanics [*Johnson and Van der Voo*, 1990] has confirmed a southerly paleolatitude of 41° S for these rocks which implies a ≥1700-km post-Ordovician displacement of the Avalon terrane with respect to the North American plate. An additional study of the Early Silurian Dunn Point Formation by *Seguin et al.* [1987], who stress the complex structural deformation of these rocks and the multi-component nature of the observed magnetization, has provided an estimated Early Silurian paleolatitude of 33° S for the Avalon terrane. In the Dunnage Zone of southwestern Newfoundland, inboard of the Avalon terrane, paleomagnetic inclinations for Late Ordovician to Early Silurian redbeds and volcanic rocks indicate a paleolatitude of 0.5° ± 6° N [*Buchan and Hodych*, 1989]. Ordovician carbonates from miogeoclinal sediments inboard of the Dunnage Zone in western Newfoundland have a characteristic magnetization (component A), interpreted to be early to mid-Ordovician in age, which corresponds to a concordant paleolatitude of 20° S [*Deutsch and Prasad*, 1987]. A detailed analysis of the Fisset Brook Formation in the Cape Breton Island region of Nova Scotia indicates that a two-polarity remagnetization was acquired in these rocks during late Early Carboniferous time [*Johnson and Van der Voo*, 1989]. An "I component" groups best at 39% unfolding, and an "H component" groups best after 60% unfolding. Paleolatitudes calculated from these secondary components show good agreement with expected paleolatitudes for Newfoundland, Nova Scotia, and New Brunswick, and are not significantly different from those expected for North America. This result implies accretion of the Avalon terrane to North America by early Carboniferous time [*Johnson and Van der Voo*, 1989].

The dual-polarity magnetization of the Upper Devonian McAras Brook Formation of northern Nova Scotia [*Stearns and Van der Voo*, 1988] was probably acquired over a relatively long interval of time, because magnetizations of both polarities are recorded in single samples. No significant inclination anomalies were found with respect to North America, and the distribution of declinations is thought to have been caused by clockwise rotation of the North American plate during Devonian time, and not by local rotations. Study of the pre-Late Ordovician Stacyville volcanics of the Lunksoos terrane in northern Maine, inferred to be an island-arc remnant, indicate a paleolatitude of 20° S for these rocks which is near the 15° S paleolatitude expected for the North American margin at that time [*Wellensiek et al.*, 1990].

The Late Ordovician Carolina Slate belt, a unit some authors have associated with the Avalon terrane, has been studied by *Vick et al.* [1987]. They interpret a characteristic component of magnetization, best-grouped after 50% unfolding, to be synfolding and Late Ordovician in age; the corresponding paleolatitude of 22° S is inferred to represent the paleolatitude of docking of the Carolina Slate belt with Laurentia. *Smith* [1987] undertook paleomagnetic study of two suites of diabase dikes in the North Carolina Piedmont, one trending N-S and the other NW, to determine whether or not the suites had been emplaced at different times during early Mesozoic rifting of the continental margin. Significantly different paleopoles for the two suites indicate that they were emplaced at different times, and also imply that the region has been tilted 15° westwards relative to the craton.

Further study of the paleomagnetism of the Late Silurian Bloomsburg and Lower Carboniferous Mauch Chunk Formations [*Kent*, 1988] has shown 23° ± 13° of relative rotation between the north and south limbs of the Pennsylvania salient. The "C component" of this study, which is best grouped upon 80% to 90% unfolding (not significantly different from 100% unfolding at the 95% confidence level), appears to record approximately half of the bending observed around the salient inferred to have occurred during the Alleghenian orogeny. *Kodama* [1988] suggests that remanence rotation due to strain during folding may result in a maximum grouping of paleomagnetic vectors at 80%-90% unfolding, possibly explaining the 80%-90% unfolding at which the Bloomsburg paleomagnetic vectors are best grouped. Clockwise rotations in declination of 32° for Appalachian units is documented by paleomagnetic study of Early Jurassic rocks in the Watchung Mountains [*Van Fossen et al.*, 1986, 1987]. It has been suggested, however, that this discordance in declination may result from differences in age for the characteristic magnetization which simply records apparent polar wander over the time interval of magnetization acquisition [*Kodama*, 1987]. To the west, *Elmore et al.* [1988] inferred 30° of counterclockwise rotation from paleomagnetic directions in overprinted Arbuckle Group limestones on the southern margin of the Southern Oklahoma Aulacogen.

New paleomagnetic studies of Paleozoic and Mesozoic units of eastern North America, not associated with far-travelled terranes, have continued to provide results of fundamental importance in interpreting the paleolatitudes of displaced terranes. *Miller and Kent* [1989*a*] determined a paleolatitude of 26° ± 12° S for the Late Ordovician Juniata Formation of the central Appalachians which indicates that this region of eastern North America was at more southerly paleolatitudes than previously estimated. This conclusion is corroborated by paleomagnetic data for Late Silurian to Early Devonian Andreas redbeds of Pennsylvania [*Miller and Kent*, 1988*b*] which imply a paleolatitude of 35° S (at 80% unfolding of component C), and by data for Devonian plutons of Maine [*Miller and Kent*, 1989*b*] which imply a paleolatitude of 42° S. These data fit a general trend of southward motion of North America from Ordovician to Early Devonian time, followed by northward drift throughout the Paleozoic [*Miller and Kent*; 1989*a*].

Recent high-quality results from the Newark Basin of late Triassic [*Witte and Kent*, 1989] and early Jurassic age [*Van Fossen et al.*, 1986, 1987; *Kodama*, 1987; *Derder et al.*, 1989; *Witte and Kent*, 1990] have provided motivation for an ambitious drilling program in the Newark rift and for detailed paleomagnetic sampling of these cores [*Olsen and Kent*, 1990]. Available results from the Newark Basin show high-latitude Middle Jurassic virtual geomagnetic poles (VGPs) [*Witte and Kent*, 1989] that are significantly different than those indicated by the PEP track-Jurassic cusp of *Gordon et al.* [1984]. *Fang and Van der Voo* [1988] studied Triassic plutons in southern Maine which indicate more southerly paleolatitudes for North America, although a tilt correction of 15° to 20° could also explain the discrepancy. The studies of *Witte and Kent* [1990] (Newark Carnian/Norian "B component", VGP latitude of 68° N) and *Van Fossen and Kent* [1990] (Moat volcanics "C component", VGP latitude of 82° N) also show high latitude VGPs, implying a Middle Jurassic loop of the North American APWP to high latitudes. These results have important implications for Mesozoic terrane displacements relative to North America and are discussed in greater detail by *Geissman and Gordon* [this issue].

South America

A compilation of paleomagnetic data for the Caribbean region, including the Greater Antilles, the Lesser Antilles, Central America, and South America, has recently been published by *MacDonald* [1990]. Although the data for this region show a good deal of scatter, general patterns are evident which can be related to tectonic processes. For the Greater Antilles, the available data from Cretaceous rocks, primarily from Jamaica, indicate counterclockwise rotation (≃10°) of these rocks with respect to North America since their emplacement; Tertiary paleopoles for the Greater Antilles are generally concordant with the North American APWP. New data for Late Cretaceous and Eocene sedimentary rocks of southwestern Puerto Rico [*Van Fossen et al.*, 1989] also indicate 45° of counterclockwise rotation relative to North

America. For the Lesser Antilles, the available data, which are primarily for Oligocene and Miocene rocks, show no trend and are basically concordant with the North American APWP [*MacDonald*, 1990]. In Central America, data for Permian carbonates of the Maya Block (southeastern Mexico) show 22° of counterclockwise rotation. Cretaceous rocks of the Chortis Block (Honduras and Nicaragua) have paleopoles indicating 50° of counterclockwise rotation and 13° of southward displacement. For northern South America, data for the few Paleozoic units analyzed, and for some Mesozoic units as well, show strong evidence of remagnetization. Other data for Mesozoic rocks show large clockwise and counterclockwise rotations [*MacDonald*, 1990].

In western Ecuador, paleomagnetic results for the early Cretaceous Pinon Formation indicate 70° clockwise rotation with respect to the South American APWP [*Roperch et al.*, 1987]. Results for Late Carboniferous (Pennsylvanian) formations in the Amotape-Tahuin Range of northwestern Peru also show 110° of clockwise rotation and evidence for northward displacement [*Mourier et al.*, 1988]. Paleomagnetic study of Early to Late Cretaceous and Paleogene volcanic, plutonic, and sedimentary rocks of the Lancones basin in the Piura province of northern Peru indicate clockwise rotation ranging from 90° for the lowermost units to 35° for the uppermost units [*Mourier et al.*, 1988]. Together, these data are consistent with a hypothesis of accretion of an Amotape-Tahuin continental terrane at the northern Peruvian margin in early Cretaceous time followed by *in situ* clockwise rotation. This pattern of clockwise rotation apparently changes to a pattern of counterclockwise rotation south of the Huancabamba deflection (4° S), perhaps related either to a change in shear regime or to along-strike variations in the amount of late Cenozoic crustal shortening [*Laj et al.*, 1989].

In the southern Andes, new data has been presented for three late Paleozoic formations exposed in Argentina [*Rapalini et al.*, 1989]. These are the Middle Carboniferous Majaditas Formation, the Early Permian Portezuelo del Cenizo Formation, and the Permo-Traissic Choiyoi Formation. The paleomagnetic data are discordant with respect to the South American APWP and can be interpreted either in terms of large clockwise rotations of these rocks during the Mesozoic and/or Cenozoic, or in terms of a displaced terrane that was accreted to the western edge of South America prior to Early Triassic time [*Rapalini et al.*, 1989]. Overprinted directions for the Permo-Triassic Pastos Blancos Formation in the central Chilean Andes have discordant declinations indicating 30° of clockwise rotation. To the west in the coastal ranges, overprint results for the coeval Cifuncho Formation also imply 30° of clockwise rotation. A prefolding magnetization for the Late Triassic Pichidangui Formation, however, indicates 15° of northward displacement between Late Triassic and Late Jurassic time [*Forsythe et al.*, 1987]. Paleomagnetic data for isotopically dated Jurassic mafic dikes and plutons in the coastal cordillera of central Chile, which cut an "exotic" terrane unlike its neighbors, indicate that accretion of this terrane occurred prior to 170 Ma [*Irwin et al.*, 1987]. Paleomagnetic studies of Lower Jurassic to Lower Cretaceous volcanic, plutonic, and sedimentary rocks in the Cordillera de la Costa of northern Chile, also indicate that there has been no significant movement of these rocks with respect to stable South America since Early Cretaceous time [*Hartley et al.*, 1988].

In general, Mesozoic and Cenozoic rocks along the active margin of western South America appear to have undergone predominantly *in situ* block rotations, whereas coeval rocks in western North America have undergone large-scale northward translations as well [*Beck*, 1988*b*]. Both the Bolivian orocline (19° S) [*Beck*, 1987], and the Magellanes orocline at the southern tip of South America, are most likely the result of small-block rotations in response to shear and not the result of actual oroclinal bending [*Beck*, 1988*b*]. In his summary of Mesozoic and Cenozoic paleomagnetic data for the western plate margin of South America, *Beck* [1988*b*] concludes that the Bonaire block of northern Venezuela and Colombia, rotated 90° clockwise and transported 1600 km northward relative to the continental interior, is one of the very few accreted terranes recognized so far in South America.

Conclusions

The accumulated paleomagnetic evidence for both the eastern and western margins of North America, as well as for the orogenic zones of South America, clearly indicates that movements of microplates and crustal blocks have played an integral role in the tectonic development of these regions. At a recent Penrose conference in Bellingham, Washington, on "Transpressional tectonics of convergent plate margins" (August 25-30, 1990) there was little disagreement that terrane movements resulted from oblique subduction and arc parallel strike-slip faulting, but the large-scale latitudinal displacements implied by some of the paleomagnetic data for the western Cordillera of North America were considered a problem by many workers. Although displacements of several thousand kilometers are generally within the limits of tangential components of convergence indicated by plate kinematic models for this region, many details of the terrane movements remain unclear. These include unidentified source regions, interactions between terranes during transport, the exact timing of transport, clear mechanisms of transport, and identifiable boundaries between some displaced and undisplaced rocks. Further paleomagnetic studies in the western Cordillera of North and South America and in the Appalachian orogen are needed to refine the elements and limits of terrane displacements, but explanations of these movements will also benefit from more detailed geologic studies in suspected source regions, in regions that can serve as modern analogs, and in the displaced rocks themselves to determine affinities bearing on the displacement history.

In addition, it is becoming increasingly clear that paleomagnetic studies of low reliability are of diminishing value. Modern reliability criteria generally stipulate that a study should include a sufficient quantity of samples to average out secular variation of the geomagnetic field, demagnetization and data analysis procedures to adequately define the characteristic components of magnetization, field stability tests and/or reversal tests to constrain the age of magnetization, and as complete an analysis of structural tilt as possible to determine the attitude of the rock unit at the time of magnetization. The latter is especially important in studies involving vertical-axis rotations of crustal blocks [see *Chan*, 1988]. Future studies, therefore, will probably include larger numbers of samples and sites, and more detailed analyses of reliability tests and paleohorizontal indicators [see *Bazenhov*, 1988], than were previously considered acceptable.

Awareness of the possibility of low-temperture remagnetization also increased during this past quadrennium with the recognition of widespread remagnetizations of late Paleozoic age in eastern North America, and of late Mesozoic age in subduction complexes along its western margin in California and Mexico. Similarity of observed paleopoles with those from the craton for a younger age than the rocks under investigation is a clear indication that remagnetization may have occurred, but deformation subsequent to remagnetization could obscure this relationship and provide positive fold tests which might be incorrectly interpreted as implying primary magnetizations. Thus, investigations contributing to the understanding of low-temperature remagnetization within orogenic zones will continue to be useful in recognizing affected rocks and in discerning the nature of tectonic and diagenetic events associated with this process. In addition, further studies recognizing and quantifying inclination errors due to compaction of sedimentary rocks, and to the extent and nature of tilting in batholithic rocks, will also be important over the next quadrennium.

As noted in previous quadrennial reports [*McWilliams*, 1983; *Hillhouse and McWilliams*, 1987], a well-constrained APWP for North America (and for other continents as well) is critical to estimating terrane displacements and microplate rotations relative to the craton, especially for times of rapid apparent polar wander, although cratonal rocks suitable for paleomagnetic study are increasingly difficult to come by [*Van der Voo*, 1989]. In the western Cordillera, refined plate kinematic models and models of coastwise transport are needed so that expected amounts of latitudinal displacement along the margin can be compared with those determined for allochthonous terranes by paleomagnetic investigations [see *Beck*, in press]. Continuum models related to large-scale plate motions, such as that proposed by *Bird* [1988], also could be useful in determining expected amounts of vertical-axis rotation for different localities at different times across the western Cordillera. The basic trends of northward displacement and clockwise rotation of terranes since mid-Cretaceous time along the North American margin have been documented, and second order trends are beginning to emerge. Terranes now appear to have been transported more along the continental margin as separate microplates than across the Pacific Basin attached to an oceanic plate, and many of the large-scale displacements (i.e., Salinia, Baja California, and Coast Plutonic Complex) appear to have occurred during Late Cretaceous to Eocene time coincident with a pulse in very rapid Farallon-North American plate convergence.

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