JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. B7, PAGES 12,479–12,496, JULY 10, 1991

On Plate Tectonics and the Geologic Evolution of Southwestern North America

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Very rapid subduction of the Farallon plate under southwestern North America between 60 and 40 Ma was accompanied by a relatively low volume of magmatism throughout the southwestern United States and northern Mexico. Between 40 and 20 Ma, when subduction slowed significantly and in one area may have even stopped, magmatism became widespread and voluminous from Nevada and Utah to central Mexico. This correlation of rapid subduction with a relatively low volume of magmatism can be explained by the observation that subduction-related andesitic arc volcanism, often formed in a Laramide-style compressional regime, is relatively low volume compared to continental volcanism. The shallow roots of arc volcanic systems are clearly exposed in the porphyry copper deposits found in currently active arcs and common throughout southwestern North America between 60 and 50 Ma. By 43 Ma, worldwide plate motions changed, the Pacific plate began moving away from North America, and subduction of the Farallon plate slowed. By around 36 Ma, the easternmost part of the East Pacific Rise, which was located between the Pioneer and Murray fracture zones, approached the trench and the young, hot, buoyant lithosphere appears to have clogged part of the subduction zone. Uplift on land became widespread. Voluminous continental magmatism formed the Sierra Madre Occidental (SMO) of Mexico, one of the largest batholiths in the world, as well as volcanic centers now exposed in the San Juan Mountains of Colorado and the Rio Grande Rift of New Mexico. Vectors of motion of the Pacific plate relative to the North American plate determined by Stock and Molnar (1988) are consistent with formation of a transtensional environment along the plate boundary sufficient to create a 100- to 200-km-wide void just landward of the old volcanic arc. While the SMO batholith was forming within this void, the Monterey and Arguello microplates just offshore to the west were broken off from the Farallon plate and rotated so that the East Pacific Rise in this immediate area became nearly perpendicular to the trench and perpendicular to the vector of motion of the Pacific plate relative to North America. Formation of the SMO batholith was followed between 24 and 20 Ma by a major increase in the rate of subduction of the Guadalupe plate, a fragment of the former Farallon plate, and by increasing mylonitization, extension, and uplift in the metamorphic core complexes that extend northwestward through southern Arizona from the northern end of the SMO batholith. The plate margin underwent another major change between 12.5 and 10 Ma when subduction again stopped, strike slip faulting became dominant along the coast, the Basin and Range Province opened, and numerous tectonostratigraphic terranes in southern California underwent large rotations. By 3 Ma a large, new terrane had been severed from North America immediately west of the SMO batholith as the Gulf of California opened. These observations can be explained by a model for the weakening and ultimate falling apart of the uppermost part of the subducted oceanic plate in the 20-30 m.y. after the end of rapid subduction. As the plate falls apart, not only is compressional stress relieved, but significant backslip along the old subduction zone is also possible, perhaps bringing blueschists rapidly upward from 20- to 30-km depths.

INTRODUCTION

Plate tectonic concepts revolutionized the earth sciences during the 1960s by providing such a cogent explanation for the origin and destruction of oceanic plates and the drift of continents that most scientists could readily perceive the utility of these new ideas. Application of plate tectonic concepts to continental geology, however, has been more difficult and remains the subject of considerable debate. The fit between data and concepts on land has not been as compelling as the fit under the oceans. One reason for this difference is that oceanic lithosphere is created at ridge crests and is not usually significantly modified, except at hotspots, until consumed at subduction zones, whereas continental lithosphere is often reworked for hundreds of millions to billions of years, and special effort must be made to separate the different tectonic events. Another reason for this difference is that there are considerably more detailed data available on land than at sea, making development of a comprehensive overview very difficult.

The approach in this paper is to show simple displays of the temporal and spatial relationships of large amounts of data. Such displays minimize assumption and interpretation and maximize our ability to focus on the overall patterns. The result is a new conceptual framework for relating detailed geologic studies with the interaction of oceanic plates along tectonically active continental margins. The framework presented in this paper is developed from the geology of southwestern North America during latest Mesozoic and Cenozoic time, when plate motions are well known. This framework will be shown in a future paper to be useful in understanding the earlier Mesozoic geology for the same region. This framework is but a suggestion or sketch of an approach that will require input from many specialists over a long period of time before we can clearly understand the processes and their mechanisms.

When relating plate tectonics to continental geology, there is a conceptual stumbling block that many of us must overcome, because there is a major difference in perception between scientists studying plate motions and those studying continental geology. Plate motions are typically described in broad, sweeping terms with processes that appear to be relatively continuous for tens of millions of years and over areas of hundreds of thousands to even millions of square kilometers. Continental geologists, on the other hand, observe changes in volcanism, tectonism, and sedimentation that occur in some cases during a million years or less and last in many cases for less than 10 m.y. These changes often occur in small areas measured in tens to thousands of square kilometers. This difference in perception appears to result primarily from a difference in method. Most plate tectonic concepts arose from geophysical data where the observing methods integrate many details over large areas. Continental geologists, however, can observe directly as much detail as desired and must integrate these details into a meaningful overview. Another factor is that when discussing trends in sparse data, geophysicists often connect data points with straight lines or else fit scattered points to lines or curves, which smooths out detail and favors sweeping generalizations. It is important to use the available geologic detail to flesh out the broad plate tectonic skeleton.

Paper number 91JB00606.

This difference in perception becomes particularly troublesome in development of models that guide our detailed work. Most research is undertaken to test some idea within a broad, widely accepted framework, and our work is done and publishable when we can relate our specific study to such a framework. Such broad concepts for continental geology have been stimulated by plate tectonic ideas and developed from restricted data sets. Many of these ideas have been very provocative and have stimulated much good research. Yet in science, few ideas survive to eternity; most develop and change. Some can become roadblocks to further thought, because if our data appear to fit them, we can complete that project, stop critical thinking, and move on to another project. I believe such roadblocks are slowing our understanding of the relation between continental geology and plate motions. For example, it is commonly assumed that subduction has been almost continuous under western North America since Late Triassic time (about 215 Ma). This assumption is unproven. Far less time is needed to subduct all plates thought to have been present in the Pacific Basin at the rates of subduction determined for the early Cenozoic. Another common assumption is that the presence of volcanic rocks, especially calc-alkaline rocks, is proof that a volcanic arc was active and thus a subduction zone must have been nearby. This assumption has been used by many to suggest that subduction zones had been active between several tectonostratigraphic terranes in western North America. However detailed geologic studies suggest that most of these terranes were never located far from the continent. Another common assumption is that major batholiths are the roots of andesitic arc volcanoes. Although many major batholiths are clearly related in space to volcanic arcs and subduction zones [*Hamilton*, 1969], no one has yet proven that they were formed at the same time. This paper emphasizes that one of the largest batholiths in the world was formed during the Oligocene in northern Mexico at least 10 m.y. after rapid subduction of the Farallon plate under the region had slowed significantly and possibly stopped.

DOES VOLCANISM RELATE TO CHANGES IN DIP OF THE SUBDUCTING SLAB?

A provocative hypothesis that has dominated our thinking about continental volcanism in the southern Cordillera for more than a decade is the suggestion that the dip of the Farallon plate being subducted beneath southwestern North America decreased gradually between 120 and 40 Ma and then increased suddenly between 30 and 20 Ma [*Coney and Reynolds*, 1977]. This concept was based on the observation that ages of igneous rocks appear to decrease progressively inland for the interval 120-40 Ma, then seaward for the interval 30-20 Ma. Given that a few shallow dipping slabs are observed elsewhere in the world where volcanism has either ended or moved inland, this idea seems plausible. A major problem arises, however, in trying to explain the nearly instantaneous "sweep" of magmatism from east to west between 30 and 20 Ma. It is not clear that plates can sink that quickly.

Coney and Reynolds used an excellent data set for rocks only in the vicinity of southern Arizona and plotted these data along an east-west profile. A similar "sweep" of magmatism is shown in Figure 1 based on a larger data base described below for igneous rocks west and south of the Great Basin. Data from the Great Basin are omitted from Figure 1 because magmatism in that region follows a distinctly different trend progressing smoothly from north to south between 43 and 17 Ma [*Stewart et al.*, 1977]. The cross section in Figure 1 is drawn parallel to the trench and nearly perpendicular to the Coney and Reynolds projection. There is an apparent "sweep" similar to that found by Coney and Reynolds, but this "sweep" extends from the northwest end of the Sierra Nevada in California to Mexico, and then back to Cape Mendocino in northern California. *Glazner and Supplee* [1982] have also argued that magmatism during the last 30 m.y. in the southwestern United States has migrated more parallel to the trench than perpendicular to it. Thus the association of the apparent "sweep" with slab dip is suspect. The Coney-Reynolds hypothesis has had a profound effect on our thinking and it correctly points out that magmatism has occurred in different regions at different times. But Figure 1 demonstrates the hazard of generalizing from limited data. Plotting the data from a limited region and for all different types of igneous rocks along a single profile and using the term "sweep" implies a linear change that tends to mask the differences in the style and chemistry of magmatism. Note in Figure 1 of this paper and especially in Figure 2 of *Coney and Reynolds* [1977] that the dated rocks cluster in time and space.

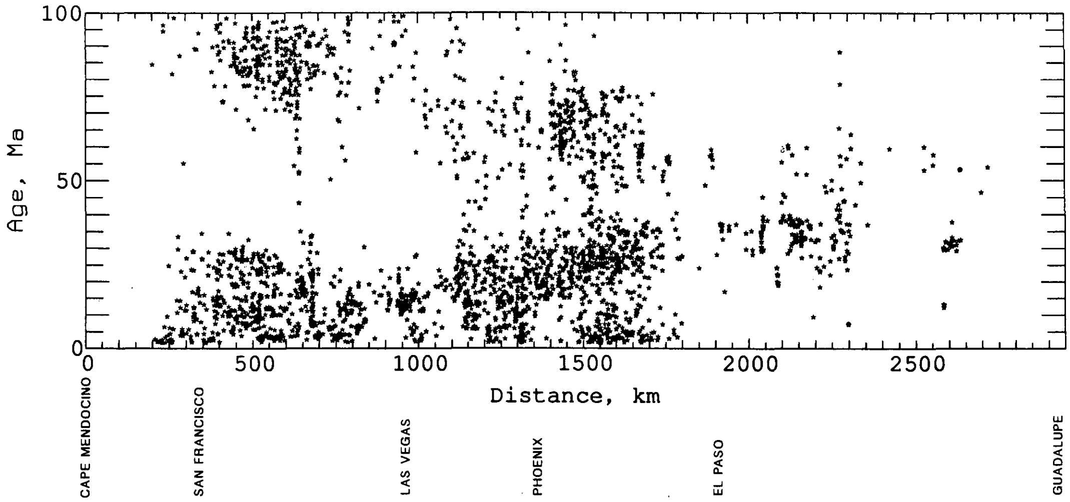

Fig. 1. Age of radiometrically dated igneous rocks from northern California to Texas projected onto a profile parallel to the plate margin from Cape Mendocino, California, to Guadalupe, Mexico, and shown as a function of distance from Cape Mendocino. The location of major cities within the United States are shown projected onto the cross section for reference. Data from the Great Basin of Nevada and Utah are excluded because they show a clear north to south migration [*Stewart et al.*, 1977] that is distinctly different from the pattern shown here.

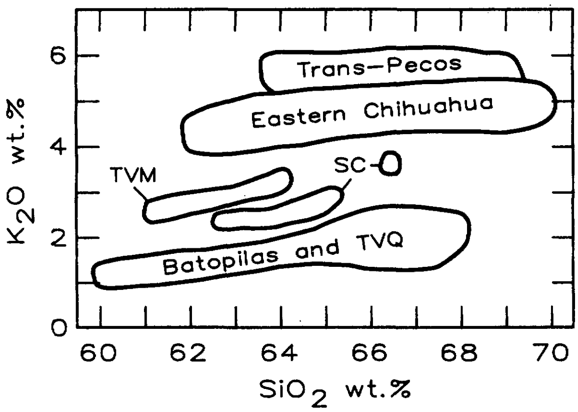

Fig 2. Variation of K_2O with SiO_2 in northern Mexico and western Texas, simplified from *Cameron and Cameron* [1986]. Data in the Trans-Pecos field are from quartz-normative hypabyssal intrusions in the Terlingua area of western Texas formed between 40 and 34 Ma. Data in the Eastern Chihuahua field are from potassium-feldspar-bearing dacites between the Trans-Pecos area and the Sierra Madre Occidental (SMO). SC stands for rocks from the Sierra los Cajones just east of the SMO and TVM is from a stratovolcano in the Miocene Sierra Santa Lucia in Baja California. Rocks studied in both of these areas are potassium feldspar free dacites. The Batopilas and TVQ field is for quartz dioritic and granodioritic plutons located just west of the SMO and formed around 83 Ma [*Bagby et al.*, 1981] and for Quaternary dacites in Baja California.

The rocks cluster geochemically also, as shown in Figure 2, where the ratio of K_2O to SiO_2 is drawn simplified from *Cameron and Cameron* [1986] for a few dacitic rocks along the Coney and Reynolds trend in northern Mexico and western Texas. The peralkaline rocks located in a small part of Trans-Pecos Texas are quite different from the dacites just to the west in Eastern Chihuahua, which are very different from dacites farther west. Volcanism of different types occurred at distinctly different times in distinctly different areas. The generalization in Figure 1 smooths out all such distinctions. As will be discussed later, there may be some validity to the dipping slab hypothesis of *Coney and Reynolds* [1977] in the immediate vicinity of the border between the United States and Mexico, but the changes are not linear, and the ideas should not be applied to most of western North America. Similar sweeping generalizations based on K_2O content [e.g., *Kuno*, 1966; *Keith*, 1978] should also be evaluated with care.

RAPID SUBDUCTION COINCIDES WITH MINIMAL MAGMATISM

One way to explore the relationship between plate motions and magmatism is to compare the rate of subduction with the volume of magmatism on the continent as a function of time. Several studies of plate motions in the northeast Pacific Ocean provide the most detailed record of Cenozoic subduction rates for any region in the world (Figure 3*a*). *Engebretson et al.* [1985] determined the relative motion between oceanic and continental plates in the Pacific Basin based on the assumption that the Pacific and Atlantic hotspots remained fixed with respect to one another. The rate of convergence of the Farallon plate with North America based on their model is shown by curve 2 in Figure 3*a*. In the case of the Farallon plate, the rate of convergence is equivalent to the rate of subduction under North America. *Jurdy* [1984] used the plate circuit approach assuming a plate boundary occurred within Antarctica prior to 42 Ma (curve 3). This proposed boundary has not been found, but *Stock and Molnar* [1987] showed that a plate boundary associated with a previously unrecognized triple junction near the Bellingshausen Sea off the coast of Antarctica would explain the discrepancy. *Stock and Molnar* [1988] computed the convergence shown in curve 1 by the plate circuit approach. All three methods agree that the highest rate of convergence or subduction of the Farallon plate under the coast of southern California and northern Mexico during the last 100 m.y. was between 60 and 40 Ma and began perhaps as early as 75 Ma.

Curve 4 (Figure 3*a*) shows the convergent component of motion of the Pacific plate relative to North America at present-day latitudes of 20°-35°N according to *Stock and Molnar* [1988]. The convergent component is calculated along an azimuth of N53°E, i.e., perpendicular to the strike of the trench. Before 42 Ma the Pacific plate was converging with North America; since that time it has been moving away. The temporal resolution in Figure 3*a* is no better than 6-16 m.y., the time between the magnetic anomalies analyzed. As more detailed data become available, it is likely that the transitions between convergence and divergence will become sharper and more numerous. For example, *Pollitz* [1986] argues for a major change in Pacific plate motion between 5 and 3.2 Ma and a slight convergence with North America since that time.

The top curve in Figure 3*b* shows the number of isotopically dated intrusive rocks per million years for the time interval 100 Ma to present in the western United States south of the Snake River Plain (43°N) and in Mexico. The 4439 dates used to compile Figure 3*b* were extracted from the U.S. Geological Survey Radiometric Age Data Bank, which was described by *Zartman et al.* [1976] when first created and which at the time of this study included most ages published before 1986. Additional data from Arizona were included from *Reynolds et al.* [1985]. Data for 79 intrusive rocks in Mexico were added by the author from the literature. Most data are based on K-Ar geochronology and have been corrected for more currently used decay constants [*Dalrymple*, 1979]. The accuracy of some K-Ar dates can be severely affected by postcrystallization reheating events. Nevertheless, if such errors are included unintentionally in the data shown in Figure 3*b*, they are not likely to change the overall shape of the distribution because there are a large number of dates, the peak in number of dates older than 60 Ma implies no widespread resetting, and a large amount of resetting is unlikely given the wide areal distribution and interspersion of rocks of widely varying age. The bottom curve in Figure 3*b* shows the number of 50 km by 50 km regions containing at least one dated rock per million year time increment. Although the relief of each curve is different, the shapes are similar, suggesting that the detail of mapping does not bias this representation of the age distribution of dated rocks.

There is a clear lull in magmatism shown by the minimum in the number of dated intrusive rocks between about 55 and 40 Ma. *Damon and Mauger* [1966] observed this same "magmatic quiescence" after what they called Laramide volcanism (75-55 Ma) and before a major increase in magmatism between 40 and 30 Ma. The relative lull in magmatism clearly coincides with the period when subduction of the Farallon plate under North America was at its highest rate. The total area of outcrop of both intrusive and extrusive rocks in the western United States is also much greater for the period 43-0 Ma than for the interval 70 and 43 Ma [*Stewart and Carlson*, 1978]. Widespread uplift and erosion in late Eocene time may have removed many extrusive rocks; uplift, however, would not remove most intrusive rocks and this inference is consistent with the increase in number of dated intrusive rocks that are older than 80 Ma (Figure 3*b*). Thus significantly greater volumes of intrusive

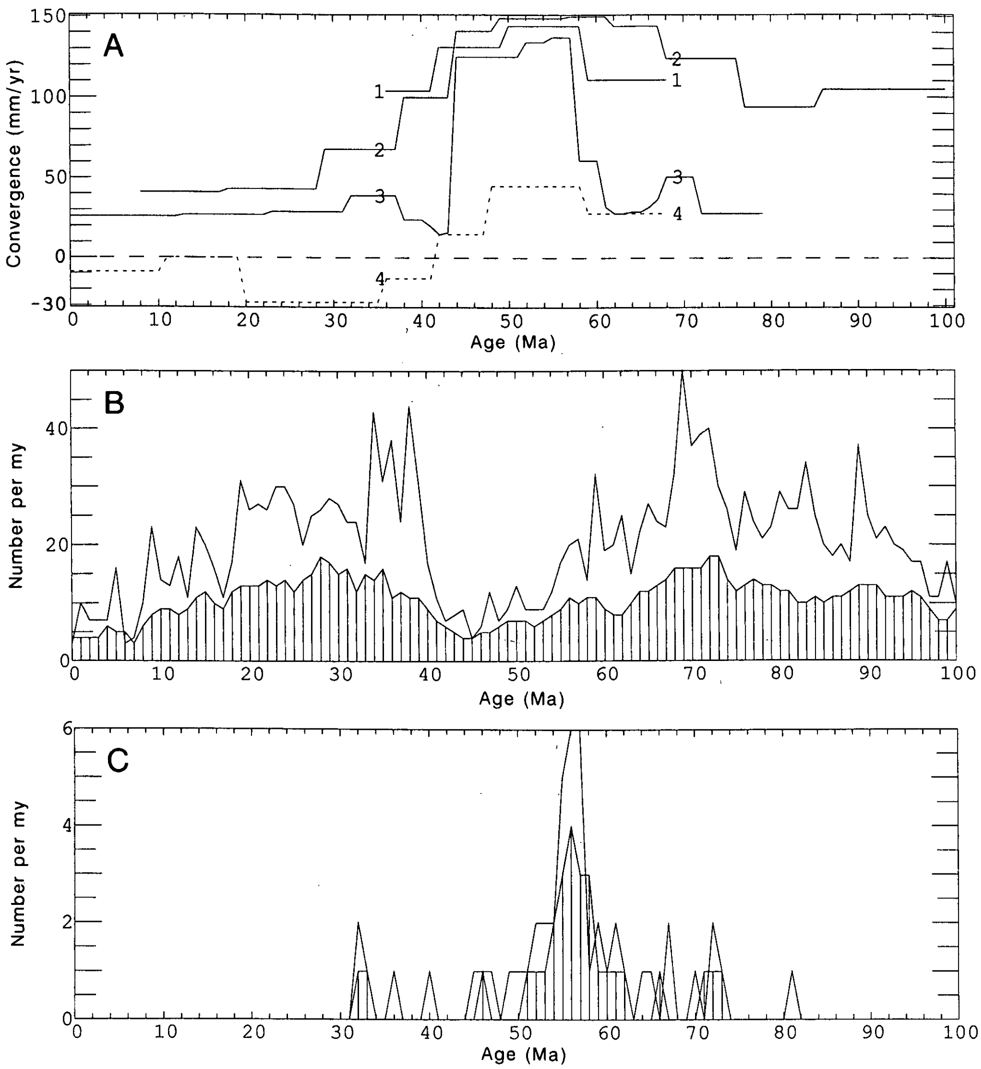

Fig 3. (*a*) The rate of convergence of the Farallon plate with northwestern Mexico as a function of age calculated by *Stock and Molnar* [1988] (curve 1), *Engebretson et al.* [1985] (curve 2), and *Jurdy* [1984] (curve 3). Curve 4 shows the convergent component of motion of the Pacific plate relative to North America at present-day latitudes of 20°N to 35°N according to *Stock and Molnar* [1988]. The convergent component is calculated along an azimuth of N53°E, i.e., perpendicular to the strike of the trench. (*b*) Top curve is the number of isotopically dated intrusive rocks per million-year time interval. Bottom curve is the number of 50 km by 50 km areas that contain at least one dated intrusive rock per time interval. The data are from the United States south of the Snake River Plain (43°N) and Mexico. The number of dated rocks is at a minimum when subduction rate is at a maximum. (*c*) Top curve is the number of radiometrically dated copper porphyry deposits in western North America per million year time interval. Bottom curve is the number of 50 km by 50 km areas that contain at least one dated copper porphyry deposit per time interval.

igneous rocks appear to have been formed before and after rather than during the period of most rapid subduction. How can this conclusion be reconciled with the large number of stratovolcanoes observed near most subduction zones today? To understand this surprising observation, we need to look at the differences between arc and continental volcanism.

ARC VOLCANISM COMPARED TO CONTINENTAL VOLCANISM

Most magmatic systems in western North America can be assigned to one of two distinct classes: arc volcanism and continental volcanism. Presently active arc systems, such as those found in the Alaska Peninsula and Aleutian Islands in southwestern Alaska or the Cascade arc extending from northern California to northwestern Washington, appear to be associated in time and space with subduction zones. Continental volcanism, such as that found at Yellowstone National Park in Wyoming, the San Juan Mountains in Colorado, the Great Basin in Nevada and Utah, or within the Rio Grande Rift in New Mexico, form farther from plate margins and often along lineaments highly oblique and even perpendicular to subduction zones [*Smith and Luedke*, 1984]. The origins of some continental volcanic systems, such as Yellowstone, have been attributed to hot spots, but this model does not appear to apply to all major continental volcanic systems. Separation of arc and continental systems on the basis of petrology is not clear. For example, andesites are most typically found in volcanic arcs, but calc-alkaline rocks are found in both systems. Basalts are common in continental rift systems but are also found in volcanic arcs. A clearer and more useful distinction can be made on the bases of morphology and magma volume.

Arc volcanic systems are numerous and widespread, but they produce relatively low volumes of extrusive rocks when compared to continental and ocean floor volcanic systems. *Crisp* [1984] concludes that the total rate of extrusion for all subduction-zone related volcanoes is 0.4-0.6 $km^3 yr^{-1}$, only 30 times the rate of extrusion from a single volcano in Hawaii. The rate of intrusion directly associated with arc volcanism is more difficult to determine. It is commonly assumed that major batholiths are formed at the same time as arc volcanoes, and Crisp finds that the volume of extrusive rocks at these volcanoes is 6-13 times less than the volume of the spatially related batholiths. But data discussed in this paper suggest that major batholiths appear to be formed at distinctly different times than most nearby arc volcanoes. Perhaps the most direct way to determine the volume of related intrusion is to measure the area of calderas that provide surface evidence for the deeper magmatic system [*Hildreth*, 1981; *Lipman*, 1984]. In arc volcanic systems such as the Aleutians, calderas average 6 km in diameter and range up to 12 km in diameter [*Smith and Shaw*, 1975]. In continental volcanic systems of western North America, calderas are more typically 20 km in diameter; the Yellowstone caldera is 85 by 45 km [*Lipman*, 1984]. Plutons and calderas in major batholiths typically have the large dimensions found in continental volcanic systems [*Pitcher et al.*, 1985; *Bateman*, 1988]. A ratio of 6 to 20 km in diameter translates into a ratio of 1 to 11 in area. For plutons of the same thickness, this relation implies a ratio of 1 to 11 in volume of magma for an arc silicic system compared to a continental volcanic silicic system. Most evidence suggests that the thickness of continental volcanic magma bodies is much greater than the thickness of arc volcanic magma bodies, making the ratio of volumes even greater. Furthermore, over periods of several millions of years, calderas in arc volcanic systems tend to be spaced 50-100 km apart along the arc, whereas calderas in many continental volcanic systems and calderas and plutons in major batholiths are typically contiguous, overlapping or even concentric when formed over a similar length of time. The relatively low volume of intrusions in arc volcanic systems is probably indicative of regional stresses, since compression encourages extrusion over intrusion [*Nakamura and Uyeda*, 1980; *Novak and Bacon*, 1986]. Compression was dominant in western North America during the period of rapid subduction, which coincides with the Laramide orogeny (approximately 75-40 Ma) [*Keith and Wilt*, 1986; *Dickinson et al.*, 1988]. The regional stresses determined from focal mechanisms of earthquakes in the vicinity of active arc volcanoes show compression and strike slip, not extension [*Molnar and Sykes*, 1969; *Ichikawa*, 1971; *Brown et al.*, 1973; *Reyners and Coles*, 1986; *Weaver and Smith*, 1983]. All of these lines of evidence suggest that stratovolcanoes in volcanic arcs have relatively low volume of extrusive rocks and directly related intrusive rocks compared to continental volcanic systems (Figure 3*b*).

There are some important exceptions to these generalities about caldera size. For example, one of the largest calderas in the world is on the volcano Toba in Sumatra. Toba is a classic volcano-tectonic depression where caldera formation is controlled to a large extent by preexisting regional faults [*Newhall and Dzurisin*, 1988]. The caldera lies in a regional, right-lateral, strike slip fault system, perhaps filling a transtensional void created at an offset in this fault system. Toba is thus intermediate between the arc and continental systems discussed above and may give some insight into the transtensional origin of major batholiths discussed below.

The shallow roots of subduction-related stratovolcanoes appear to be exposed today in copper porphyry stocks that have been studied in considerable detail because they are the source for most of the copper mined in the world [*Sillitoe*, 1973; *Branch*, 1976; *Sutherland Brown*, 1976; *Hollister*, 1978; *Damon et al.*, 1983]. Porphyry copper deposits are most common in the circum-Pacific "ring of fire" and in other regions where subduction was active at the time the deposits were formed [*Argall and Wyllie*, 1983]. The porphyry deposits are often comagmatic with andesitic volcanics. The mineralization usually forms near calc-alkalic plutons of the granodiorite-quartz monzonite range and, in some areas, around quartz-free diorite intrusions [*Hollister*, 1978]. The copper sulfides typically fill steeply dipping joints and faults, often grids of conjugate fractures, that surround and pass through the intrusion. Strike-slip faults, commonly found in the vicinity of volcanic arcs [*Jarrard*, 1986], often play a major role in concentrating the sulfides. The mineral deposits appear to be concentrated and deposited by saline hydrothermal waters at temperatures below 600° C and at depths of the order of 2 km. The age of mineralization is essentially synchronous with the age of the intrusion [*Hollister*, 1978]. Breccia pipes probably related to explosive release of magma or gases are common in these porphyry deposits. Most authors conclude that the porphyry copper deposits were formed at shallow depth under andesitic stratovolcanoes. In southwestern North America, most of these deposits were formed between 65 and 50 Ma (Figure 3*c*), the period of most rapid subduction (Figure 3*a*). There is some suggestion from improved dating methods that they may have formed over a narrower span of time. These deposits, like volcanic arcs, lie along lines located typically less than 300 km landward of an active trench at the time of formation (V in Figure 4). Porphyry copper deposits younger than 10 Ma are found in presently active volcanic arcs such as the Andes of South America and the Aleutian arc in Alaska [*Hollister*, 1978]. These clear spatial and temporal correlations suggest that the occurrence of many copper porphyry deposits may be linked to major, rapid subduction nearby. Lack of such deposits in areas that have not been deeply eroded might then be assumed to imply a different regime where subduction either did not exist or was of a different nature, such as slow and sluggish or highly oblique. While this relationship needs further verification, it does suggest a first-order way to determine when old subduction zones were most active.

Major batholiths do not appear to be roots of andesitic volcanic arcs. Although they are often found in the vicinity of andesitic volcanic arcs, they do not appear to be comagmatic. Detailed mapping of wall rocks in the Sierra Nevada of California [*Bateman*, 1988] and in the Coastal Batholith of Peru [*Pitcher et al.*, 1985] shows that andesitic arc volcanics tend to form at times that are distinctly different from the times of major plutonism. Such major batholiths are made up of several intrusive episodes, during each of which large numbers of contiguous and overlapping plutons are often formed within a few million years. Plutons directly related to arc volcanism, on the other hand, tend to be more scattered among the country rock. In the Coastal Batholith of Peru, large caldera systems exposed at the surface can be seen to grade downward into plutons of similar horizontal dimensions. These plutons and calderas are most commonly tens of kilometers in diameter, similar in size to calderas associated with continental volcanism and distinctly different from calderas found in most active volcanic arcs. While the depth of erosion varies throughout major batholithic systems, the Mesozoic Sierra Nevada batholith in California provides excellent exposures typical of the midlevel parts of batholithic systems. The predominantly Late Cretaceous Coastal Batholith of Peru shows what the upper parts of a batholithic system must look like. The uppermost levels are clearly exposed in the Oligocene Sierra Madre Occidental (SMO) silicic volcanic province in Mexico. The SMO contains one of the largest continuous expanses of silicic rocks in the world, extending 1200 km from Guadalajara to southeastern Arizona and southwestern New Mexico (Figure 4) and forming a high plateau reaching elevations of 3000 m with an area of nearly 300,000 $km.^2$ The SMO compares in scale with the Coastal Batholith of Peru (1600 km long) [*Pitcher et al.*, 1985] and the Sierra Nevada batholith of California (400 km long) [*Bateman*, 1983]. Although little detailed mapping has been done within the SMO, *Swanson and McDowell* [1984] infer that it may contain as many as 350 calderas by analogy with the 20 times smaller San Juan volcanic field in Colorado. The SMO is closely related in time and space to the "Great Ignimbrite Flareup" in the southwestern United States and to major activity at calderas in Colorado, Arizona, and western Texas (39-26 Ma [*Lipman*, 1984]). Morphologically and petrologically it is more similar to continental volcanic systems than to arc volcanic systems. What was the plate tectonic environment in which this major batholith formed?

SPATIAL AND TEMPORAL RELATION BETWEEN PLATE MOTIONS AND MAJOR CENOZOIC VOLCANISM

The position of the Pacific plate relative to North America at 42 Ma is shown in Figure 4 by rotating the Pacific plate 24.55° counterclockwise about a pole at 57.84° N 68.72° W based on the plate circuit calculations of *Stock and Molnar* [1988]. The uncertainties in the relative position are of the order of ±100 km. Magnetic anomalies shown begin at anomaly 18 (42 Ma) on the east and extend back to anomaly 34 (84 Ma) south of the Pioneer fracture zone. Many authors [e.g., *Champion et al.*, 1986; *Hagstrum et al.*, 1987] have proposed that several terranes moved along the boundary between the Pacific and North American plates in the last 42 m.y. Only one of the proposed motions has been restored in Figure 4 by rotating land west of the San Andreas fault and west of the Gulf of California 4.69° counterclockwise about a pole at 48.62° N 75.15° W. This Euler rotation closes the mouth of the Gulf of California by 308 km

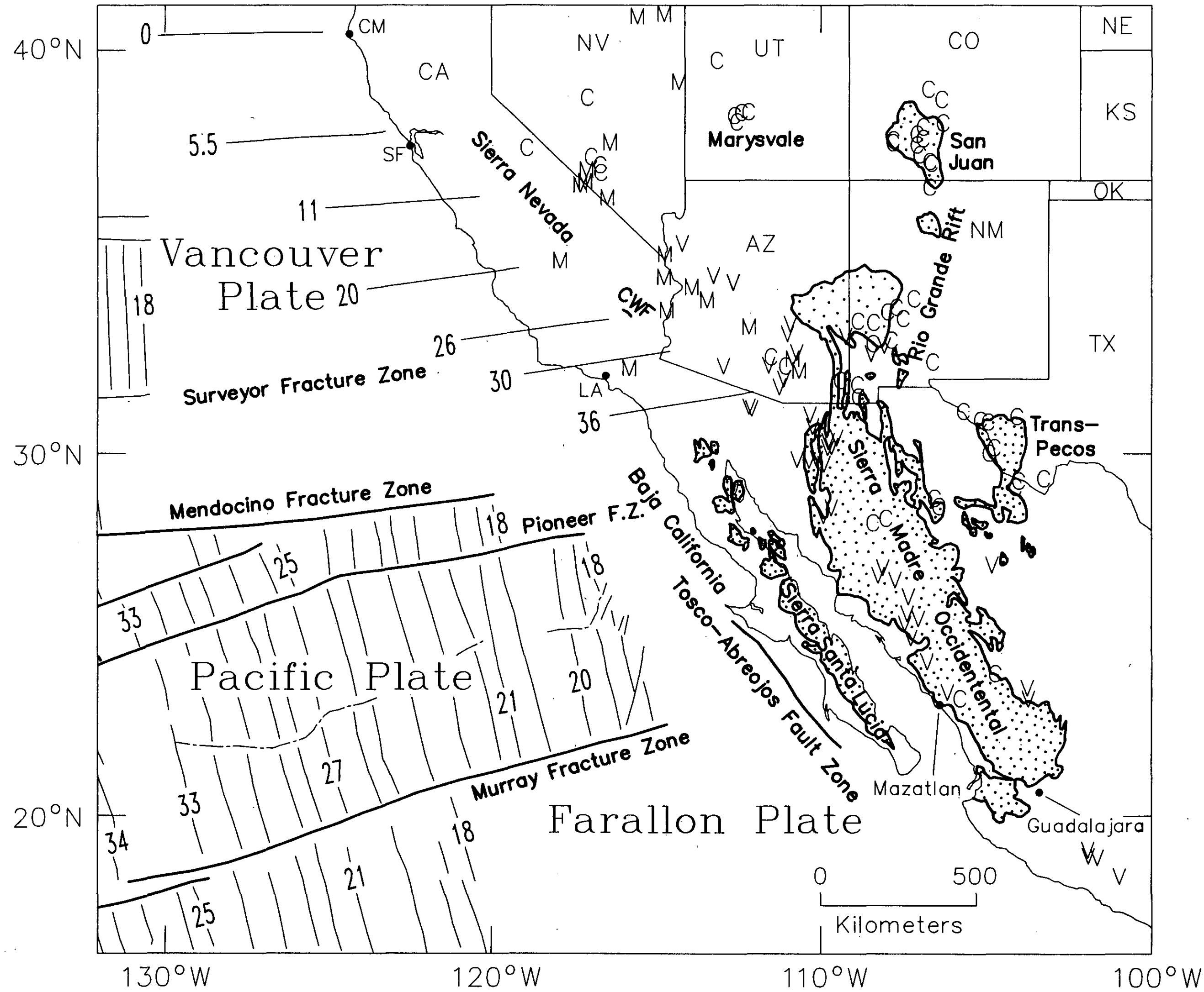

Fig 4. Map of the southwestern United States and northern Mexico showing the location of the Sierra Madre Occidental batholith and related volcanic fields, major calderas (C), porphyry copper deposits (V), and major Miocene metamorphic core complexes (M) in the southern Arizona region. Only features younger than 71 Ma are shown. CM, Cape Mendocino; LA, Los Angeles; and SF, San Francisco. Land west of the San Andreas fault has been rotated to close the Gulf of California. The magnetic anomalies on the Pacific plate that formed before 42 Ma (anomaly 18) [*Atwater and Severinghaus*, 1989] are shown in their position relative to North America at 42 Ma using vectors calculated by *Stock and Molnar* [1988]. A short segment of the Mendocino fracture zone west of Cape Mendocino, California, is shown rotated to its former positions at 36, 30, 26, 20, 11, and 5.5 Ma. Stippling shows major outcrop areas of primarily Tertiary volcanic rocks in the vicinity of the SMO [*King*, 1969]. CWF is the Clemens Well fault.

along an azimuth of 127° and removes 290 km of displacement on the San Andreas fault in the Salton Trough [*Stock and Hodges*, 1989]. The position of a 500-km-long segment of the Mendocino fracture zone, currently located just west of Cape Mendocino in northern California, is also shown in Figure 4 rotated by the *Stock and Molnar* [1988] poles for the times 36, 30, 26, 20, 11, and 5.5 Ma. This segment includes lithosphere south of the Mendocino escarpment with ages ranging from 33 Ma on the west to 27 Ma on the east. The spatial overlap of these lines on the continent prior to 10 Ma is caused by extension within the Basin and Range and opening in the vicinity of the Sierra Madre Occidental, discussed below. Neither of these extensions has been restored in Figure 4, as the amounts of extension are still unclear. The plate circuit calculations used by Stock and Molnar, however, are specifically formulated to determine the net convergence and extension across the entire width of the margin between stable North America and the oceanic plates. A small portion of the overlap may also be caused by motion along faults other than the San Andreas that have not been restored in Figure 4.

Many features displayed in map view in Figure 4 are shown as a function of time and latitude in Figure 5. The northward migration of the nearly east-west trending Mendocino fracture zone relative to a fixed North America is shown by the line extending diagonally across Figure 5 from 0 to 68.5 Ma. This line is calculated from the *Stock and Molnar* [1988] poles of relative plate motion. The changes in slope of the line illustrate the changes in rate of northward movement of the Pacific plate relative to the North American plate. The azimuth and rate of motion of the Pacific plate relative to North America for different time periods are shown near the base of Figure 5 and as vectors in Figure 6 (for the southern point on the Pacific

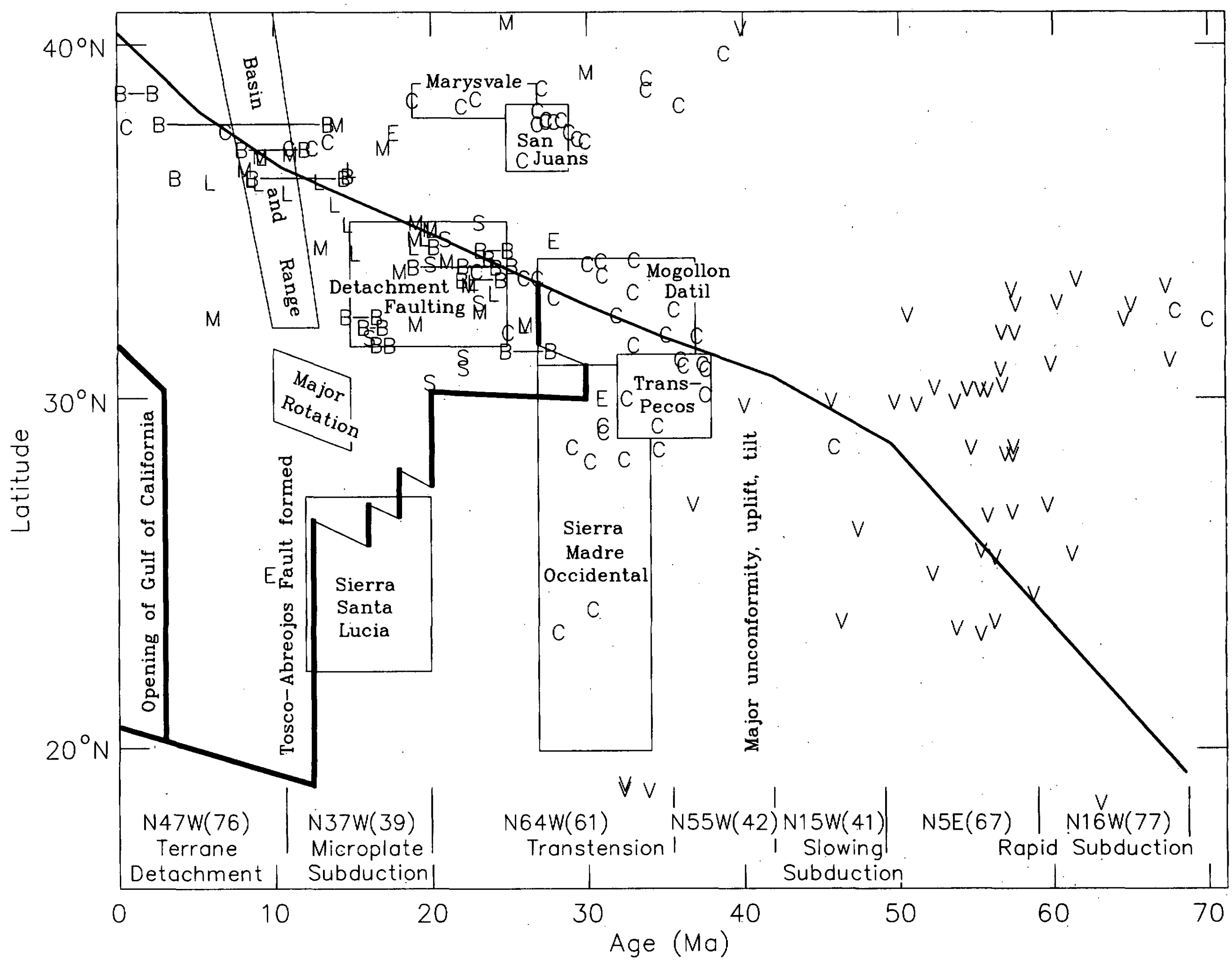

Fig 5. Tectonic features related to the interaction of the Pacific plate with southwestern North America shown as a function of age and current latitude. This figure adds the time dimension to Figure 4. The main features are described in the text. The latitude of the Mendocino escarpment as a function of time is shown by the diagonal line beginning at 40.4°N and 0 Ma. Heavy lines show the age of the youngest magnetic anomalies presently exposed off the coast and the latitude of the ridge at the time of formation. The heavy line at 3 Ma shows the oldest magnetic anomalies within the Gulf of California. Symbols indicate calderas (C), copper porphyry stocks inferred to be the locus of stratovolcanoes (V), change to northeast-southwest extension (E), onset of low-angle normal faulting (L), and volcanism near the Mendocino Triple Junction (lines terminated with B). The extents of several volcanic fields are shown. Detachment faulting is in the metamorphic core complexes of southern Arizona and southeasternmost California (M). The major rotation is for the western Transverse Ranges. If rotations east of the San Andreas fault in the Mojave were included the box would extend farther northward. Basin and Range marks the time and location of major, high-angle, normal faulting. The rapid onset of subsidence in major sedimentary basins (S) is from *Atwater* [1989] and the latitudes are determined using her reconstruction of faulting along the margin. The azimuth and rate in millimeters per year of the Pacific plate relative to a point in southwestern North America are shown near the bottom of the figure together with a description of the major tectonic regime.

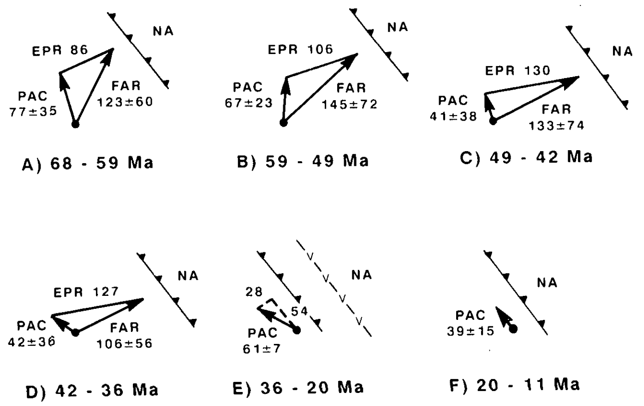

Fig 6. A vector analysis of plate motions relative to southwestern North America based on finite rotations calculated by *Stock and Molnar* [1988] for northern Mexico and regions to the west. NA, North America; EPR, East Pacific Rise; FAR, Farallon plate; and PAC, Pacific plate. The strike of the trench along the southwestern coast of North America is assumed to be N37° W and is shown by barbed lines. Rates are in millimeters per year. The Sierra Madre Occidental (SMO) formed during time E along the northeast edge of the line of andesitic volcanoes (V) that had been active primarily between 65 and 50 Ma. When the SMO was formed, the motion between the Farallon and North American plates had slowed, the motion between the Monterey and North American plates may have stopped, and the Pacific plate was moving away from North America, creating a vector component of opening (Figure 8). Time F shows the strike slip motion between the Pacific plate and North America in northern Mexico. Farther south, subduction of the Guadalupe plate was underway at the same time.

plate listed in Table 15 of *Stock and Molnar* [1988]). The possible errors for these numbers become large for times prior to 35 Ma. Current locations of many of the plates and magnetic anomalies described in this paper are shown in Figure 7.

A major plate reorganization in the Pacific Basin between 87 and 84 Ma resulted in fragmentation of the Farallon plate into three pieces [*Mammerickx and Sharman*, 1988]. One piece became attached to the Pacific plate. The second piece became

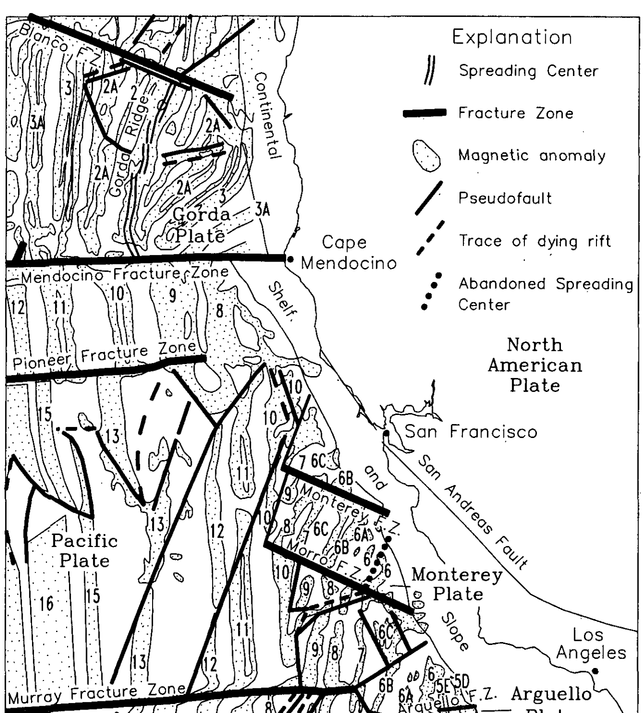

Fig 7. The current location of magnetic anomalies, fracture zones, major faults, and ridge crests off the coast of California.

the Kula plate moving to the north-northwest. The third was the remaining Farallon plate, which began to accelerate and move northeastward under North America. On land, these plate tectonic realignments correspond in time to a fundamental turning point in Cordilleran tectogenesis [*Coney*, 1972] and the onset of the Laramide compression in the western United States, which began in Arizona at 88 Ma and migrated northward to Wyoming by 72 Ma [*Keith and Wilt*, 1986]. Major compressional, Laramide-style deformation had begun in eastern Mexico by late Maastrichian time (about 70 Ma) and possibly earlier [*Suter*, 1984]. By 60 Ma and possibly 70 Ma, subduction was proceeding at a rate of 13-15 cm/yr (Figure 3*a*). Andesitic-dacitic stratovolcanoes became active from northwestern Arizona to Guadalajara, Mexico. Porphyry copper deposits in this region (V in Figures 4 and 5) are dated primarily between 45 and 75 Ma [*Damon et al.*, 1983] (Figure 3*c*). Some stratovolcanoes formed on lowlying Cretaceous limestone, but the same area soon formed an elevated ridge shedding sediments both to the northeast and to the southwest [*McDowell and Clabaugh*, 1979]. Intrusive and extrusive rocks from these stratovolcanoes are widespread southwest of the Sierra Madre Occidental (SMO) but are far less common to the northeast.

Another significant plate reorganization occurred at 55 Ma, when the Vancouver plate was created from the part of the Farallon plate north of the Pioneer fracture zone [*Rosa and Molnar*, 1988]. The strike of the Surveyor, Mendocino, and Pioneer fracture zones rotated 20° clockwise [*Atwater*, 1989]. The Kula plate rotated rapidly counterclockwise [*Lonsdale*, 1988], and the Aleutian Ridge was formed above a subduction zone that detached a piece of the Kula plate to become the basement for the Bering Sea [*Scholl et al.*, 1983]. The time of this plate reorganization coincides with the onset of the voluminous Challis volcanics in the northwestern United States and southernmost British Columbia [*Armstrong*, 1978] and the peak in the number of dated porphyry copper deposits in southwestern North America (Figure 3C).

The easternmost protrusion of the Pacific plate in the North Pacific during early Tertiary time lay between the Pioneer and Murray fracture zones. This protrusion and the related part of the East Pacific Rise approached the coast of Mexico by 43 Ma (Figure 4). Either for this reason or because of other boundary conditions such as a global plate reorganization related to the collision of India with Asia [*Searle et al.*, 1987], the motion of the Pacific plate slowed, and its direction of motion relative to southwestern North America changed from N15° W to N55° W (Figure 6*d*) as reflected in the bend of the Hawaii-Emperor seamount chain [*Duncan and Clague*, 1985]. Motion of the Pacific plate relative to southwestern North America changed from convergence to divergence or more specifically from right-lateral transpression to right-lateral transtension (Figures 3*a* and 6*d*). Thus, while the East Pacific Rise continued spreading at about the same rate, convergence of the Farallon plate with North America slowed (Figure 6*d*) beginning around 43 Ma.

By 43 Ma, arc volcanism in western Mexico and Arizona had decreased significantly, and uplift and block tilting were widespread, forming major angular unconformities throughout Mexico and much of the western United States [*McDowell and Clabaugh*, 1979; *Glazner and Loomis*, 1984; *Crowell*, 1987]. Southern Arizona became part of a broad erosional surface that shed sediments northward to Utah and Colorado [*Shafiqullah et al.*, 1980]. Inland, along the projection of the Pioneer fracture zone and due east of the easternmost protrusion of the Pacific plate (Figure 4) in the Trans-Pecos section of west Texas, minor volcanism, including basalt flows and andesitic, peralkaline rhyolitic, and syenitic intrusions, formed perhaps as early as 48 Ma but clearly by 43 Ma [*Henry and McDowell*, 1986]. Considerable alkali-calcic and alkalic volcanism dominated this region between 38 and 32 Ma. Similar but less alkalic volcanism formed the Mogollon-Datil volcanic field of Arizona and New Mexico a few million years later as the segment of the Pacific plate between the Mendocino and Pioneer fracture zones moved to the northwest (Figures 4 and 5). Andesitic volcanism started near the SMO before 38 Ma and was followed beginning around 36 Ma by eruption of voluminous rhyolite ash flows [*Wark et al.*, 1990]. By 30 Ma, some basaltic andesite was extruded near the same eruptive centers.

Oceanic lithosphere was still being created offshore until sometime after 30 Ma, as indicated by magnetic anomalies on the Pacific plate (Figure 7). The latitude at the time of formation of the youngest magnetic anomalies presently observed along the coast is shown by the thick lines in Figure 5, based on the map of *Atwater and Severinghaus* [1989] and rotated to the latitude at the time of formation using the poles of *Stock and Molnar* [1988]. These thick lines identify the oldest times that oceanic lithosphere was still being created and thus the youngest times that strike slip faulting is likely to have begun at specific latitudes. For the Gulf of California, latitudes at the time of formation of the oldest magnetic anomalies (3 Ma) are shown to emphasize the timing of the formation of the gulf.

Typically, the magnetic anomalies within the Pacific plate lie approximately parallel to the coast. However, the ocean floor currently southwest of San Francisco, California, was created at a ridge striking nearly normal to the trench. This ridge formed as the Monterey and Arguello microplates broke from the Farallon plate by 29 Ma and continued spreading until 20 Ma (Figure 7) [*Wilson*, 1988; *Atwater*, 1989]. These anomalies are represented by the thick horizontal line in Figure 5 at 30° N. The distribution of these magnetic anomalies and their relation to North America and to microplates compare directly with the magnetic anomalies formed around the Gorda Ridge (Figure 7) just north of the Mendocino fracture zone during the last 3 m.y. South of the Monterey and Arguello microplates, the magnetic anomalies are fan shaped just like the anomalies formed in the last 3 m.y. around the mouth of the Gulf of California, reflecting pivoting subduction [*Menard*, 1978]. Thus a tectonostratigraphic terrane, possibly the Yager terrane southeast of Cape Mendocino [*Blake et al.*, 1988], may have been severed from North America beginning around 29 Ma, just as land west of the San Andreas fault is now moving northwestward relative to North America. The strike of these magnetic anomalies is perpendicular to the vector of relative motion shown in Figure 6*e*, and these anomalies account for approximately 400 km of motion between North America and the Pacific plate from 29 to 20 Ma.

While subduction slowed drastically in the vicinity of the Monterey and Arguello microplates, subduction of the Farallon plate to the south and the Vancouver plate to the north slowed only by 15%. Between 36 and 20 Ma total spreading of the East Pacific Rise just north of the Mendocino fracture zone and well south of the Murray fracture zone was at an average total rate, i.e., across both sides of the ridge, of 136 mm/yr along an azimuth of approximately N85° E from the map of *Atwater and Severinghaus* [1989]. Adding this vector to the PAC vector in Figure 6*e* implies subduction continued at an average rate of 90 mm/yr.

The magnetic anomalies thus document major changes in plate motions west of Mexico at 43 and 29 Ma. Between 44 and 35 Ma (anomalies 19 to 13), a series of curving, toothlike disjunctures formed south of the Murray fracture zone and several substantial pieces of the Farallon plate in this region were transferred to the Pacific plate (Figure 7) [*Atwater*, 1989]. The Monterey and Arguello microplates broke from the Farallon plate by 29 Ma. The Sierra Madre Occidental (SMO) began forming at 34 Ma and was largely complete by 27 Ma with activity at individual centers lasting typically 3-5 m.y. [*McDowell and Clabaugh*, 1979]. A few significantly younger ignimbrites (23 Ma), perhaps not related to the main intrusive phase, are found at the southern end near Mazatlan, Mexico. Evidence for andesitic stratovolcanoes in the region of the SMO is rare from 43 Ma until between 24 and 20 Ma when stratovolcanoes began erupting along the main cordillera of Baja California, forming rocks that have been called the Comondu Formation by *Hausback* [1984] and more restrictively called the andesitic volcanic rocks of Sierra Santa Lucia by *Sawlan and Smith* [1984] (Figures 4 and 5). Eruption of these volcanoes ceased around 12 Ma when subduction was terminated by formation of the Tosco-Abreojos transform fault along the southwest coast of Baja California (Figure 4) [*Spencer and Normark*, 1979; *Mammerickx and Klitgord*, 1982].

From this general overview, it is clear that many major changes in volcanism relate in time and space to major changes in plate motion. Andesitic arc volcanism is well documented geologically in southwestern North America during the same two periods of time when plate convergence and subduction under this region are well documented from plate motion calculations. The SMO, on the other hand, was formed between these two periods of subduction when andesitic volcanism was rare and during the period of greatest divergence of the Pacific and North American plates (Figures 3*a* and 6*e*). The SMO is substantially different in chemistry and morphology from arc volcanic systems and is most similar to continental volcanic systems as described above.

FORMATION OF A MAJOR BATHOLITH WITHIN A TRANSTENSIONAL ZONE

The SMO was formed between 34 and 27 Ma, the same time that the ocean floor between magnetic anomalies 12 and 7 was being formed. By 29 Ma and directly west of the northern part of the SMO (Figure 4), the Monterey and Arguello microplates broke from the Farallon plate, rapidly rotating 30° clockwise [*Mammerickx and Klitgord*, 1982; *Atwater*, 1989] so that a segment of the East Pacific Rise (Figure 7) became perpendicular to the vector of relative motion between the Pacific plate and the North American plate (Figure 6*e*). Spreading on this ridge segment continued at an average total rate of 55 mm/yr until 28 Ma (anomaly 8) and at a rate of 36 mm/yr from 28 to 20 Ma (anomaly 6). *Stock and Molnar* [1988] calculate that the average rate of motion of the Pacific plate away from southwestern North America was 61 mm/yr between 36 Ma (anomaly 13) and 20 Ma (Figure 6*e*). There was at least one major change in plate motions along the margin of North America during this 16-m.y. interval, but, for comparison with their number, the average total rate of spreading from 36 to 20 Ma was 50 mm/yr. Thus most of the motion between the Pacific and North American plates in this region was taken up by spreading on the ridge between the Pacific and Monterey plates. Only 11 mm/yr of motion would have had to occur between the Monterey and North American plates. This motion might have occurred along the subduction zone or along another zone of weakness.

Young oceanic lithosphere, with a thin, hot upper mantle component, is more buoyant than older oceanic lithosphere and is thus more difficult to subduct. *Oxburgh and Parmentier* [1977] calculated that the oceanic lithosphere becomes gravitationally unstable upon the asthenosphere when it is 40-50 m.y. old. As a mid-ocean ridge approaches a trench and the average age of the subducting slab decreases, subduction slows [*Molnar and Atwater*, 1978; *Jarrard*, 1986]. *England and Wortel* [1980] discuss the effects of lithospheric age on subduction and show that there is a critical point, at which the average age of the slab is of the order of 40-70 m.y., where ridge push and slab pull may not be able to overcome resistive forces and subduction will stop unless an additional horizontal compressive stress is applied. Using the FAR vectors in Figure 6, we can estimate that at least 4000 km of Farallon plate was subducted under North America between 68 and 36 Ma. Thus the subducted slab would have contained oceanic lithosphere similar in age to that of the Pacific plate from anomaly 13 south of the Pioneer fracture zone to a point midway between the island of Hawaii and the junction of the Emperor and Hawaiian seamount chains. Half of the subducted Farallon lithosphere was formed between 84 and 36 Ma. The age of the other half of the subducted lithosphere is not clear because it most likely formed between 118 and 84 Ma when the magnetic field did not alternate. Using 118 Ma and 36 Ma as the age range of the subducted lithosphere, then a very rough estimate of the average age of the subducted lithosphere at 36 Ma is of the order of 40 m.y.

The subduction of young buoyant lithosphere is likely to have caused the uplift observed in northern Mexico and the southwestern United States after 43 Ma and could be expected to reduce the forces favoring subduction. As discussed above, andesitic arc volcanism in southwestern North America largely ceased between 43 and 20 Ma, implying either a major change in subduction or possibly termination of subduction. Thus it seems likely that part of the Farallon plate became stuck to the North American plate in northern Mexico sometime between 36 and 29 Ma, and that plate motion was able to resume by breaking the stuck parts of the plate to form the Monterey and Arguello microplates. Which part of the North American plate could have been severely stretched by this process?

The upper edge of a subducting oceanic plate typically passes below the lower edge of the continental plate under the volcanic arc [*Isacks and Barazangi*, 1977]. The volcanic arc is also thought to form a zone of lithospheric weakness. Grabens often form behind or within the arc, as can be seen today, for example, in El Salvador, the Cascade Range of Oregon, and on the North Island of New Zealand. The Basin and Range Province of the southwestern United States formed primarily just landward of the volcanic arc. Thus the region just landward of the volcanic arc is a natural place for a transtensional shear zone to develop during such times of stretching and is precisely the region where the SMO formed. A tectonic boundary near the SMO separating westernmost Mexico from North America is also suggested from paleomagnetic data collected in Baja California and Sinaloa, the region just east of the Gulf of California, for the time period 45 and 34 Ma [*Hagstrum et al.*, 1987].

Whether subduction of the Monterey and Arguello microplates actually stopped does not really bear on the necessity for extension, as shown in Figure 8. If we assume that the motion between the Monterey and North American plates was taken up on the subduction zone (S) and on a zone of weakness behind the volcanic line (V), then the difference in motion between the Pacific and North American plates of 61 mm/yr less the rate of spreading of 50 mm/yr, or 11 mm/yr of divergence, would equal V - S. Thus any subduction that continued would increase the amount of divergence required behind the volcanic arc. Another possibility is that the 11 mm/yr was provided by backslip on the subduction zone, but the evidence for backslip, discussed below for a different time period, is not found in the geologic record during the time the SMO was formed. The cartoon in Figure 8 is simplified because the vector of motion between the Pacific and North American plates (N 64° W) strikes 21° more westerly than the strike of the trench (N37° W). Thus the 11 mm/yr of opening would be transtensional with a component of 5 mm/yr perpendicular to the trench and 9.8 mm/yr along the trench. Between 36 and 20 Ma, the anticipated opening perpendicular to the trench would be 80 km. If subduction continued, the opening would be greater. The SMO is 200 km wide including extrusive lava flows and ignimbrites. The underlying batholith probably is much narrower and probably involves some crustal assimilation. The opening is most likely to have occurred between 34 and 27 Ma when the SMO was forming and when the Monterey and Arguello microplates were being severed from the Farallon plate (anomalies 12 through 8, Figure 7).

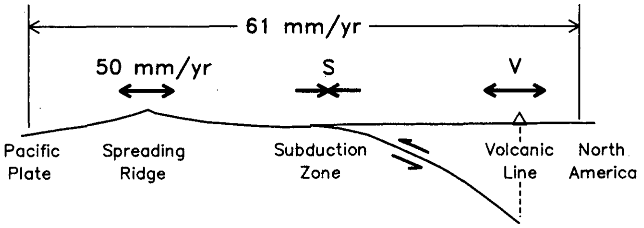

Fig 8. The motion of the Pacific plate away from North America equals the spreading at the East Pacific Rise minus subduction of the Monterey plate plus extension of the continental boundary probably near the volcanic line.

The sea floor magnetic anomalies and the plate motions during this important time need to be examined in much more detail, but it is clear that extension of the continental margin must have occurred. Extension of northern Mexico has been documented by *Stock and Molnar* [1988]. In their reconstructions, the apparent overlap of the Pacific plate onto Mexico was 150 ±75 km at 35.58 Ma, 340 ±200 km at 30.03 Ma, and 260 ±75 km at 25.82 Ma. This apparent overlap, as discussed above, is most likely caused by later extension of the Basin and Range, extension to allow formation of the SMO, and possible movement of small terranes along the coast. The timing and amount of each of these three possible processes have yet to be determined, but the data allow extension of as much as the 200-km width of the SMO between 34 and 27 Ma. A classic problem in explaining the origin of batholiths has been to define how the space for these huge bodies was created [*Read*, 1950]. The location of the SMO in space and time is wholly consistent with a transtensional origin for this massive volume.

Such transtensional stretching may be occurring today east of the Sierra Nevada in California. The Gorda plate, northwest of Cape Mendocino, is presently rotating in a manner similar to the rotation of the Monterey and Arguello microplates by 29 Ma [*Wilson*, 1989]. The southern edge of the Gorda plate, or southernmost part of the Juan de Fuca plate, as inferred by *Wilson* [1986], strikes at about S60° E. Following this strike from Cape Mendocino southeastward across California leads to Long Valley caldera, a recently active 20 km by 35 km continental type volcanic system lying just east of the old volcanic arc [*Bailey et al.*, 1976]. Panamint Valley and Death Valley, to the southeast are currently undergoing right-lateral transtension [*Stewart*, 1983; *Jones*, 1987]. Calderas tend to form inland from the Mendocino Triple Junction as it moves northward (Figure 5). The current tectonic regime is quite similar to what I infer the regime may have been around 30 Ma except the motion of the Pacific plate relative to North America was 20° more westerly at that time. This means that there was a greater component of extension and the non subducting boundary directly connecting the oceanic plates to North America was much shorter at that time. Both differences are likely to have made the stretching of the North American plate in northern Mexico more intense in Oligocene time than now.

If major transtension occurred throughout northwestern Mexico in middle Oligocene time, then where are the ends of this zone? The southern end is poorly exposed beneath the younger Trans-Mexico volcanic belt. The northern end is located at the south end of the Rio Grande Rift, as will be discussed in the next section. It is possible that much of the opening motion was taken up on a right-lateral strike slip fault connecting the northern tip of the SMO near the border of New Mexico, Arizona, and Mexico with the coast of southern California. *Smith* [1977] and *Joseph et al.* [1982] propose that about 120 km of right-lateral strike slip occurred during Oligocene to early Miocene time on the San Juan-Chimeneas-Morales-Blue Rock-San Francisquito-Fenner-Clemens Well fault. This fault lies in an east-southeasterly line through southern California when Miocene and younger offset is reversed on the San Andreas and related faults. The Clemens Well fault segment is shown as CWF in Figure 4. Extension of this proposed fault into the intensely deformed rocks of southern Arizona is less clear, but *Titley* [1976] describes clear evidence of major discontinuities along northwest-southeast trends that were active in Mesozoic time and were probably reactivated during Late Cretaceous-Early Tertiary or slightly more recent times. On the other hand, if the Clemens Well fault is eventually shown to turn more southerly, parallel to the coast, and especially if the age of movement can be shown to be less than 27 Ma, then this fault system would compare more directly to the San Andreas fault system but would be related to northward migration of the Mendocino Triple Junction in latest Oligocene and earliest Miocene time (33.6°N in Figure 5).

THE TRANSTENSIONAL ORIGIN OF OTHER BATHOLITHS

A batholith has been defined as "a large, generally discordant, plutonic mass with more than 100 km^2 in surface exposure and is composed predominantly of medium- to coarse-grained rocks of granodiorite and quartz monzonite composition" [*Gary et al.*, 1974, p. 62]. In this paper the term major batholith refers to such rocks where the surface exposures are of the order of 10,000 km^2 or larger. Major batholiths are commonly an aggregate of many separate episodes of intrusion. Clearly, batholiths can come in many shapes and sizes and have many origins [*Buddington*, 1969; *Pitcher*, 1979]. A transtensional origin may not apply to all batholiths, but it may provide important insight into the origin of some major batholiths near subduction zones. The clear separation in time between subduction-related arc volcanism and batholith formation shown in Figures 3 and 5 has also been suggested, as discussed above, from detailed mapping of wall rocks in the Sierra Nevada of California and in the Coastal Batholith of Peru. Direct evidence for transtension is difficult to find without knowing the motions of the plates while these batholiths were forming. *Hutton* [1982] has documented one example of apparent transtension in the Donegal granite of Ireland, but these types of structures are not widely noticed. They appear to be formed during a relatively late cooling stage. Similarly, forceful intrusion of some plutons is well documented (see summary by *Pitcher* [1979, p. 645]) but is generally rare and typically late stage. *Castro* [1986] describes early to late stage structures related to a dextral shear zone in the formation of a Carboniferous batholith in Spain. *Busby-Spera and Saleeby* [1990] and *Saleeby* [1991] document right-lateral strike slip contemporaneous with intrusion of granitic magmas in the southern Sierra Nevada of California around 80 Ma. Batholith emplacement at shallow depth generally appears to be a passive process with little deformation. The boundaries of individual plutons are sharp. The zone of contact metamorphism is normally very narrow. Pieces of wall rock are sometimes found in the granite near the wall with little deformation or rotation. Such passive intrusion is exactly what one would expect if the magmas are filling an extending void rather than forcing open the space. The general lack of brittle, mesoscopic structures related to transtension may indicate that transtension occurs at an early stage, before the magma has cooled. On a regional scale, transtensional motion is suggested most directly by the general elongation of plutons along the strike of the batholith. *Tobisch et al.* [1986, p. 65] argue that the eastern Sierra Nevada has a "complex history related to extensional tectonics." The wall rocks and pendants throughout the Sierra Nevada give clear evidence of strike slip faulting at least between and perhaps during plutonic phases [e.g., *Dunne et al.*, 1978; *Nokleberg*, 1983]. Recent work by *Hutton et al.* [1990] shows how the rapakivi granite suite in southern Greenland intruded an active extensional shear zone. There is still much mapping or remapping to be done before we can reliably determine the detailed mode of emplacement from the local structures. Individual plutons may show a great deal of variety, since the component of extension may vary from significant to insignificant to even mild compression. The observed plate motions strongly suggest a transtensional origin for the SMO, one of the largest batholiths in the world. The possibility of such a transtensional origin should be considered carefully for other major batholiths formed in locations and at times when plate motions are not as well known.

EXTENSION, SCHISTS, AND METAMORPHIC CORE COMPLEXES

At the time the SMO began forming, there was a fundamental change in southwestern North America from Laramide-style compression to extension and ultimately to widespread detachment faulting and rifting. Northeast-southwest directed extension had become dominant in the Rio Grande Rift and in western Texas by 32 Ma [*Aldrich et al.*, 1986]. This was about the time that the Pacific plate began moving most rapidly away from North America (Figure 3*a*, curve 4) as discussed above (Figure 6*e*). The initial opening of the Rio Grande Rift, which extends NNE from the northern end of the SMO (Figure 4), is likely to have formed in an attempt to accommodate within the North American plate major transtensional opening of the SMO in Mexico. Another extensional domain that dominated the geology of southern Arizona during approximately the same time interval is found in the metamorphic core complexes (MCC) (M in Figures 4 and 5). The temporal and spatial relations shown in Figures 4 and 5 provide an interesting perspective on the origin of these complex terranes.

The MCC lie in a narrow zone, only 50-100 km wide, that extends northwestward from the northern tip of the SMO and around the southwestern and western edges of the Colorado Plateau [*Wust*, 1986; *Howard and John*, 1987]. The MCC show evidence of profound regional extension on a severely stretched and necked basement [*Davis and Coney*, 1979; *Rehrig*, 1986]. *Reynolds and Spencer* [1985] and *Howard and John* [1987] find evidence for a minimum of 50 km of extension in the vicinity of the MCC. This intense deformation was punctuated by an unusually thorough tectonic denudation, which is defined as a tectonically induced intracrustal thinning [*Dokka et al.*, 1986]. Major Tertiary extension within these MCC began around 35 Ma [*Rehrig*, 1986] with mylonitization along azimuths from north to north-northeast [*Reynolds et al.*, 1986] and appears in time and space to be related to the proposed transtensional opening of the SMO. By 25 Ma, mylonitization was along azimuths close to N60° E [*Wust*, 1986], the direction that the Farallon plate had been subducting under North America (Figure 6). The mylonitization was followed by detachment faulting between 25 and 15 Ma. The timing of faulting on the major Whipple Mountains detachment can be narrowed to between 20 and 18 Ma [*Davis and Lister*, 1988], the time that spreading perpendicular to the trench ceased between the Monterey and Pacific plates [*Atwater*, 1989]. The nature of this faulting implies that extension in the lower plate outpaced extension in the upper plate [*Rehrig*, 1982]. Lower plate mylonitic gneisses were drawn upward and out from under upper plate rocks [*Davis and Lister*, 1988]. The MCC were active at the northern edge of the subducted Monterey plate as the Mendocino Triple Junction moved northward (Figure 5) [*Glazner and Bartley*, 1984] and thus may reflect differential motion between the impeded subduction zone to the south and the continuing subduction zone to the north.

One of the most troubling aspects of the geology of the MCC and the entire southern Arizona-southern California extensional corridor is evidence for little erosion of the porphyry copper deposits that were formed at depths of about 2 km located adjacent to the MCC where evidence suggests 10-15 km of uplift [*Howard and John*, 1987]. Just to the west, in southern California, the Pelona, Orocopia, and Rand schists of southern California appear to have been uplifted by as much as 20-30 kilometers [*Ehlig*, 1981]. These schists are believed to have been metamorphosed in a subduction zone between 59 and 52 Ma [*Ehlig*, 1981] and perhaps as early as 74 Ma [*Dillon et al.*, 1990], the same age as the porphyry copper deposits. The metamorphic assemblage of the schists shows that uplift must have been more rapid than by normal rates of erosion in orogenic belts. Furthermore, there is no evidence for the amount of sediment that would have had to have been eroded to expose 20- to 30-km-deep schists. The best evidence for the major motion along the Vincent, Chocolate Mountains, Orocopia, and Rand thrusts associated with the schists involves transport of the upper plate to the northeast [*Haxel and Dillon*, 1978; *Dillon et al.*, 1990]. There has been much debate over whether these thrusts, which typically dip westward, represent a northeastward or southwestward dipping subduction zone [*Jacobson et al.*, 1988]. Some uplift appears to have occurred during formation as shown by a younging of the schist down section [*Dillon et al.*, 1990], but the most recent uplift could be associated with Tertiary detachment faulting [*Frost and Martin*, 1983]. What process could explain these disparate data?

At some point, plates subducted under western North America must have detached and fallen into the mantle, because with the exception of a small [*Humphreys et al.*, 1984; *Humphreys and Clayton*, 1990] and possibly young [*Bird and Rosenstock*, 1984] plate under the Transverse Ranges of southern California there is little evidence that old plates are still attached to the continental lithosphere [e.g., *Grand*, 1987]. Old plates are unlikely to melt in the upper mantle because most of the plate consists of refractory peridotite whose low-melting components have been extracted to form oceanic crust [*Dickinson and Luth*, 1971]. The disintegration of the subducting plate did not occur simply by subduction of the East Pacific Rise because there is clear evidence that pieces of Farallon plate and thus segments of the East Pacific Rise remain along much of the coast of California [*Atwater and Severinghaus*, 1989]. The old plate must fall apart by a combination of processes such as being pulled apart by plate motions, pulling itself apart by becoming denser, or being weakened by an increase in heat.

As the hot lithosphere near the ridge crest approaches the subduction zone, the heat in the crust above the downgoing slab must increase, leading to weakening of the continental and oceanic crusts. But the major strength of the plate is in the subcrustal peridotites that make up most of the plate and that seem to have adequate strength under tension even when formed near the oceanic ridge. The strength, and elastic thickness, will be small at the ridge but increasing with time since formation [*Parsons and Sclater*, 1977]. Thus while hot, young lithosphere entering the trench may effect deformation of the continent, it is not clear to me that the strength of the slab will decrease; only the rate of cooling and thus the rate of increase in strength will be slowed.

The buoyancy of the slab will change, however. With the passage of time, the average age of the subducted slab will increase, increasing the forces favoring renewed subduction [*England and Wortel*, 1980]. While the plate may be cooling near the trench and heating at depth, we can estimate the time constant involved for a change in buoyancy. *Parsons and Sclater* [1977] show from ocean floor depth and heat flow data that oceanic lithosphere requires about 70 m.y. to lose most of its heat of formation, but half of the cooling occurs within the first 20 m.y. The rate of cooling will decrease when the hot slab is subducted under the continent, but most cooling will still occur within the order of 20 m.y. As subduction had slowed significantly by 36 Ma, the pieces of the Monterey and Arguello microplates should have cooled enough by 20-10 Ma to have significantly reduced their buoyancy.

As the slab weight increased, it is conceivable that the stuck slab could have been pulled apart and begun moving again. Pulling apart of the slab would relieve the compressional stresses associated with subduction, because subduction is primarily driven by the negative buoyancy of the sinking slab. Relief of compressional stress could even lead to backslip and uplift along the old subduction zone, bringing high-grade metamorphic schists to the surface very rapidly. *Davis and Lister* [1988] date this backslip between 20 and 18 Ma, the time of the termination of spreading associated with the Monterey and Arguello microplates. It is conceivable from the vectors in Figures 6*e* and 7 that if the lower part of these microplates fell into the mantle, the upper part may have been pulled up out of the trench as the Pacific plate moved away from North America. Falling apart of the subducted slab and backslip of the upper remaining part of this slab are likely to cause major distension of the continental lithospheric flap above the former subduction zone and between the trench and the volcanic line. The most pervasive failure is likely to be near the volcanic arc, typically located above the place where the upper part of the subducted slab loses contact with the continental plate. The MCC lie close to the old volcanic arc but were formed at mid crustal depths, much shallower than the former subduction zone, which is typically of the order of 100 km below the volcanoes [*Isacks and Barazangi*, 1977]. Thus deformation in the MCC would relate to significant distension and upwelling of deep lithosphere. Fresh asthenosphere could then move up under this distended section of the continental plate fostering magmatism integrally involved with or just preceding the development of many metamorphic core complexes [*Rehrig*, 1986]. Uplift of the Colorado Plateau and vicinity could have resulted from this effective delamination of the lithosphere, which is different in detail but similar in effect to the delamination described by *Bird* [1979]. Such distension and upwelling is likely to cause the old subduction surface near the former trench to bulge upward, changing dip from northeast to southwest as observed along the Vincent, Chocolate Mountains, Orocopia, and Rand thrusts.

Many details of geology in the MCC suggest some relationship to the former subduction zone and the volcanic arc. For example, *Rehrig* [1982, 1986, p. 100] emphasized that "compressional, shear-induced mylonites of Laramide age crop out in the Cordillera; in fact, they seem to be retained within MCC exposures." While these mylonites are not likely to have formed along the subduction zone, they could be formed by forces on the continental lithosphere imposed by the subduction process that serve to thicken the crust [*Bird*, 1984, 1988]. *Coney and Harms [1984] and Spencer and Reynolds* [1990] argue that during subduction in Laramide time "crustal telescoping resulted in an overthickened plateaulike crustal welt along the Cordilleran hinterland. During Cenozoic time this gravitationally unstable mass spread laterally, resulting in deep-seated crustal extension" [*Coney and Harms*, 1984, p. 550]. *Rehrig* [1986, p. 116] concludes that the MCC "originated in areas controlled by ... (1) high heat flow or intrusion, (2) regional extension, (3) previously formed, low-angle anisotropic fabrics, and (4) presence of metamorphic or magmatically supplied fluids." These features imply proximity to magma or upwelling of asthenosphere. The intense deformation in a narrow zone near the MCC was contemporaneous with or immediately preceded opening of the Basin and Range. There is much field work to be done, but the important conclusion at this point is that the geology of the MCC documents a major extensional event beginning at about the time when the SMO began forming farther to the south and becoming dominant at about 20 Ma. The extensional event in the MCC took place just east of the easternmost protrusion of the Pacific plate and either above the northern boundary of the Monterey microplate or possibly above the microplate that might have been between the Mendocino and Pioneer fracture zones on the old Vancouver plate. The MCC also occur at the northwestern end of the SMO batholith (Figures 4 and 5) and may give some insight into structure of the lithosphere beneath the SMO [*Haxel et al.*, 1990]. The MCC do not occur along the whole SMO, but others may be covered by it. They do extend northwestward into the Panamint Valley area of California and Nevada (latitude 36.5° N in Figures 4 and 5) and generally become younger to the north, suggesting a relationship to the northward moving Mendocino Triple Junction. MCC north of Nevada appear to be related to major plate changes in the Pacific Northwest around 55 Ma. These temporal and spatial relationships imply that the MCC in the southern Arizona region resulted from failure of the continental lithosphere related in some way to the interaction of the Pacific plate and the subducted Monterey plate with North America. Considerably more data are needed to work out the details of this interaction.

Dixon and Farrar [1980] propose reverse motion on a subduction zone, which they call eduction, as a way of bringing blueschists to the surface. Their model depends on the East Pacific Rise being subducted under North America, which the magnetic anomalies show did not happen. *Cloos* [1982, 1986] proposed that the subducting plate can drive a forced convection in the accreted sediment pile, driving blueschists, eclogite, and other melange material back to the surface. *Platt* [1987] proposed that underplating of the accretionary wedge can extend the wedge horizontally and allow blueschists to rise to shallow depths. It is not clear in both of these steady state models why blueschists would tend to cluster in age [*Dobretsov et al.*, 1987; *Blake et al.*, 1988].

CONVERSION FROM SUBDUCTION TO A TRANSFORM MARGIN

About 25 Ma, when formation of the SMO had ended, a major plate reorganization west of the coast of Mexico [*Mammerickx and Klitgord*, 1982] formed the Guadalupe plate from the remaining Farallon plate. The stratovolcanoes of Sierra Santa Lucia in Baja California (Figures 4 and 5) show that subduction of this old piece of the Farallon plate was well underway south of 27° N in Figure 5 by 20 Ma and possibly as early as 24 Ma [*Sawlan and Smith*, 1984]. More scattered calc-alkalic and basaltic volcanism erupted in northern Baja California and migrated northward along the coast, apparently with migration of the Mendocino Triple Junction [*Johnson and O'Neil*, 1984; *Fox et al.*, 1985] (Figure 5, lines terminated with B). At 22±2 Ma very rapid subsidence to bathyal depths deepened or created sedimentary basins along the coast including the Los Angeles, Ventura, San Joaquin, Cuyama, Santa Maria, Bodega, and Point Arena basins (S in Figure 5) [*Crowell*, 1987; *Dickinson et al.*, 1987; *Hendrix and Ingersoll*, 1987; *Atwater*, 1989]. Formation of these basins coincides in time with resumption of subduction to the south, onset of low-angle faulting inland (L in Figure 5 [*Glazner and Bartley*, 1984]), and onset of major caldera activity to the northeast in the Marysvale field of Utah (c in Figure 5 [*Lipman*, 1984]). Backslip on the subduction zone may have played a role in the formation of these basins. The plate reorganization at 25 Ma was associated with a fundamental change in tectonics on the continent.

The next fundamental change in tectonics also correlates with a plate reorganization between 12.5 and 10 Ma [*Mammerickx and Klitgord*, 1982] when the eastern boundary of the Pacific plate jumped eastward from a large segment of the East Pacific Rise to the Tosco-Abreojos fault formed in the Borderland west of Baja California [*Spencer and Normark*, 1979, 1989]. Large blocks of southern California, especially those now in the vicinity of the western Transverse Ranges, rotated 50° to 60° clockwise between 15.2 and 10 Ma [*Luyendyk et al.*, 1980; *Hornafius et al.*, 1986]; extension began in the region that would later become the Gulf of California [*Stock and Hodges*, 1989]; rapid subsidence began or resumed in the San Joaquin, Santa Cruz, and Ridge basins [*Crowell*, 1987]; and high-angle normal faulting began in the Basin and Range [*Zoback et al.*, 1981]. Strike-slip faults such as the San Gabriel became active [*Crowell*, 1982]. The western few hundred kilometers of the continent were extended and broken up in what may have been the final disintegration of the subducted plate discussed above. Strike-slip faulting appears to have become active at least along the southern half of the 2000-km-long plate boundary from the Mendocino fracture zone to the southern tip of Baja California. Strike-slip faulting along the coast of southwestern North America prior to about 12 Ma, has yet to be demonstrated. The total displacement of the Pacific plate relative to southwestern North America since 26 Ma is approximately 1160 ±100 km along an azimuth of N49° W ±4° according to *Stock and Molnar* [1988]. Less than 30% of this displacement can be accounted for by the San Andreas fault, and most of that, at least in southern California, must have been in the last 5 m.y. with the opening of the Gulf of California. Another 11% can be contributed by the San Gregorio-Hosgri fault [*Graham and Dickinson*, 1978]. The balance must have been taken up on a myriad of smaller faults off the coast or on land [e.g., *Howell et al.*, 1974; *Kies and Abbott*, 1983; *Bird and Rosenstock*, 1984; *Ross*, 1984], by slip along the old subduction zone, and by deformation over broad areas such as the Basin and Range. Termination of subduction west of northern Mexico around 12 Ma coincides with the onset of major extension of the margin causing much of the overlap shown in Figure 4, rotation of crustal blocks, and development of deep basins. All of these processes probably contributed to the release of tectonostratigraphic terranes from the continent. At 10 Ma, all of California and Baja California was nearly severed from the stable portion of North America by extension in the Basin and Range. Perhaps the regions north of San Francisco were pinned against the continent by ongoing subduction of the Vancouver plate. By 3 Ma the part of the continent just onshore from where the Pacific plate had come closest to North America at 42 Ma (Figure 4) was ruptured along the San Andreas fault and the Gulf of California, creating a tectonostratigraphic terrane that is headed northward to join other terranes perhaps formed earlier by a similar process. Another way of viewing this process is that the part of the Pacific plate boundary that came closest to North America moved from the trench inland closer to the old volcanic arc, severing much of the previous crustal wedge above the subducting slab from the continent.

As we proceed to study the details of the relationship between the formation of the SMO, the Gulf of California, and the terrane west of the San Andreas fault, it is important to realize that the northwestward motion of the Pacific plate may not have occurred at a smooth rate as shown in Figure 5. The motion is calculated for specific time intervals by averaging across many magnetic anomalies. The instantaneous motion may be jerky or irregular, especially along the plate margin where both elastic and nonelastic deformation can be important. The clearest evidence for irregular motion is found in volcanism along the margin that remains active in one region for a while and then jumps considerable distance to the next region rather than forming a series of closely spaced volcanic vents that progress steadily northwestward with time (lines terminated with B in Figure 5) [*Johnson and O'Neil*, 1984; *Fox et al.*, 1985]. About 300 km of motion took place on the San Andreas fault system in the 5-6 m.y. since the opening of the Gulf of California. Thus 5-6 m. y. ago the Mendocino fracture zone was just north of San Francisco. The Sonoma Volcanics and the Tolay Volcanics of *Morse and Bailey* [1935] in this area formed between 13.6 and 3.2 Ma [*Fox et al.*, 1985]. Thus, if volcanism is related to the proximity of the triple junction, there may have been a 10-m.y. hiatus in northward motion. Arc volcanism since 10 Ma in the Sierra Nevada to the east is also limited to the region north of the latitude of San Francisco [*Luedke and Smith*, 1981]. A large hiatus is also suggested by the voluminous sediments of the Delgada Fan just south of the Mendocino fracture zone, which had to come from some large river such as the Sacramento [*Hein*, 1973]. Major fans occur in specific locations rather than being spread evenly along the whole coast. Calderas inland also are formed during discrete intervals. Thus northward motion may have been significantly faster since 3 Ma than during the 10-m.y. period before 3 Ma. It was during this younger interval that the Gulf of California formed and half of the plate under the Aleutians was subducted. Such rapid changes in the rate of northward motion would help explain the difference between the motions measured in California today and those predicted from global plate motions by *Minster and Jordan* [1978]. These changes also provide a new point of view with which to approach studies of the sudden changes in fault patterns and crustal structure in the San Francisco Bay Region.

A TECTONIC MODEL

The data displayed in Figure 5 can be fit into a simple sequence of events shown schematically in Figure 9 with times applicable to the region of southwestern North America. Subduction proceeds at rates as high as 10-20 cm/yr and stratovolcanoes form an arc behind the trench (Figure 9*a*). Many of the roots of these volcanoes are exposed later in porphyry copper deposits. At least in the case discussed here, stresses in the vicinity of the arc are compressive perpendicular to the trench, resulting in Laramide-style compression. Subduction slows as the average age of the subducted slab decreases, and the increasing buoyancy of the slab may cause its dip into the mantle to decrease. When a segment of the mid-ocean ridge arrives near the trench, subduction slows (Figure 9*b*), but spreading at the ridge may continue if the plate motions change to include a component of relative extension. Subduction in regions where the ridge is not quite as close to the trench may also slow because the oceanic plate on the opposite side of the ridge from

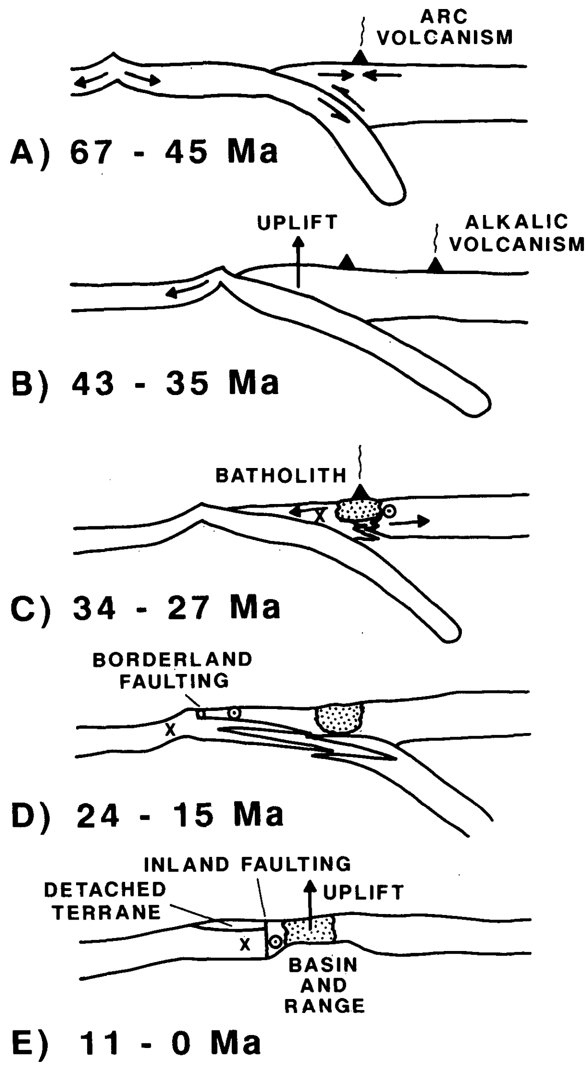

Fig 9. A model of the interaction of a mid-ocean ridge with a trench where the ridge strikes at a high angle to the trench. See description in text. Shear parallel to the trench is shown by dots (tips of arrows) and crosses (tails of arrows).

the continent cannot continue to converge upon the continent without additional compressive forces. Peralkaline volcanism erupts well inland from the region of closest approach of the ridge. Within 10 m.y., back arc extension or transtension develops creating space for the formation of a large batholith (Figure 9*c*). Rifting of the continent, e.g., the Rio Grande Rift, occurs outside of the region of closest approach of the ridge. The ridge appears to die, and, within about 20 m.y. after subduction slowed, the subducted plate has cooled and increased in density enough that it begins to pull itself apart and the older deeper segment falls into the mantle (Figure 9*d*). The falling apart of the plate releases compressional stresses across the margin, and mylonitization and detachment faulting become dominant above the zone where the slab had been. A piece of the slab may separate and rotate, forming a microplate such as the Monterey plate. Backslip may occur along the old subduction zone either because of this release of compressional stress or if the oceanic plate is being drawn away from the continent because of other boundary conditions. Strike-slip faults form in the continental borderland near the trench. Subduction can now speed up in nearby segments of the trench where the ridge is still well offshore and active. With continued strike slip faulting, the transform boundary jumps inland (Figure 9*e*) above the deep-seated plate boundary, transferring pieces of the continental flap above the old subduction zone to the oceanic plate and in the process rotating many of these fragments. A simple example of such a migration of the transform boundary has been discussed by *Zandt and Furlong* [1982] and *Furlong* [1984] in northern California: migration of motion from the San Andreas fault to the Hayward and Rodgers Creek faults. Motion along the transform boundary may ultimately lead to the onset of subduction in the future, for example by sliding an active trench along the plate boundary. Otherwise the margin may become passive, to be ruptured at some time in the future. Around 11 Ma (between Figures 9*d* and 9*e*) the boundary between the North American and Pacific plates appears to have broken up, indicating that the strength of the boundary went through a minimum. At this time, rapid motion of either plate would be possible if boundary conditions elsewhere along the plates were appropriate.

The simple sequence of events in Figure 9 may apply to other regions and time periods but can be complicated laterally along the margin by the different times of arrival of different segments of the ridge and by different possible motions of the oceanic plates. The observation that the Pacific plate began moving away from North America at 43 Ma profoundly influenced the sequence of events since that time and may have been caused by a worldwide change in plate motions rather than by processes along the western margin of the North American plate. There is still much work to be done before the physical processes involved in this evolution can be understood.

CONCLUSIONS

The most rapid subduction of the Farallon plate under southwestern North America occurred between 60 and 40 Ma, the time of a widespread relative lull in magmatism in the western Cordillera south of Oregon and Idaho. Arc volcanic systems are typically widespread but of low volume. The shallow roots of andesitic arc volcanoes associated with subduction appear to be most clearly exposed in the porphyry copper deposits that form a line through western Mexico and southern Arizona. Around 43 Ma, subduction slowed and the Pacific plate began moving away from North America. Directly inland from the point of closest approach of the eastern edge of the Pacific plate, peralkaline volcanism began in western Texas. Regional compression during subduction turned to extension beginning around 32 Ma, and continental magmatism became dominant during the "Great Ignimbrite Flareup" from the Sierra Madre Occidental (SMO) in Mexico to the Mogollon-Datil and San Juan volcanic fields in Arizona, New Mexico, and Colorado. These major batholithic systems apparently filled a transtensional void created by the most westward motion of the Pacific plate known during any time in the Cenozoic. The batholiths are related in space to the old subduction zone, but they formed when subduction had slowed significantly or even stopped. They were most voluminous in the region east of where the Pacific plate first came close to North America.

The SMO, one of the largest batholiths in the world, ends to the north in the Rio Grande Rift and in a line of metamorphic core complexes (MCC) that trend northwestward across Arizona and into California. Mylonitization in the MCC began during the time period of formation of the batholith, and the crust under the batholith may be similar to the highly distended and detachment faulted crust in the MCC. Mylonitization turned into widespread detachment faulting between 25 and 15 Ma, especially between 20 and 18 Ma, and major sedimentary basins suddenly formed around 22 Ma. These events were perhaps related to a pulling apart of the subducted plate and backslip on the old subduction zone, ultimately bringing blueschists rapidly to the surface. Between 12.5 and 10 Ma the old plate margin fell apart with the onset of major strike slip faulting and the opening of the Basin and Range. Strike-slip faulting and extension developed inland, transferring the outer parts of the margin to the oceanic plate and thus creating tectonostratigraphic terranes. This pattern provides a model to relate continental geology to plate tectonics that will need to be refined and tested.

Acknowledgments. The concepts presented in this paper were developed over a 7-year period during an extensive review of the literature on plate motions and the geology of western North America. I wish to thank the staff of the USGS library in Menlo Park for their efficient and courteous help. Don Huber, Dick Armstrong, Ric Wilson, Dick Marvin, and Keith Howard assisted in compilation of a data base for ages of more than 15,000 igneous rocks in western North America. During these 7 years I wrote several manuscripts but did not publish them because my ideas were in a constant state of flux. My thoughts were stimulated and focused by thoughtful reviews of these papers from Dick Armstrong, Paul Bateman, Bob Christiansen, John Crowell, Bill Dickinson, Warren Hamilton, Dave Howell, King Huber, Porter Irwin, Walter Mooney, Chris Stevens, Jack Stewart, Art Sylvester, Bob Wallace, Ray Wells, and Mary Lou Zoback. Discussions with Donny Hutton, Wallace Pitcher, George Plafker, and Vic Seiders were also valuable. This paper was substantially improved from reviews by Paul Stone, Mary Lou Zoback, Gordon Haxel, Bob Simpson, JoAnn Stock, and King Huber. Thanks to Tanya Atwater, Paul Bateman, Bob Christiansen, Peter Lonsdale, Jack Stewart, and JoAnn Stock for making papers available prior to publication. Special thanks to Bob Wallace and Karen Ward whose continuing support have made this paper possible.

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(Received March 16, 1990;
revised February 4, 1991;
accepted February 26, 1991.)