TECTONICS, VOL. 3, NO. 2, PAGES 115-119, APRIL 1984

CORRELATION OF PLATE MOTIONS WITH CONTINENTAL TECTONICS: LARAMIDE TO BASIN-RANGE

D. C. Engebretson

Department of Geology, Western Washington University

A. Cox and G. A. Thompson

Department of Geophysics, Stanford University

Abstract. Some of the major tectonic and magmatic events of the last 150 Ma in the Western Cordillera can be correlated with a new model for the displacement histories between western North America and adjacent oceanic plates. Sierra Nevada plutonism ended and Laramide compression began during increasingly rapid convergence of the Farallon plate with North America and during a moderate increase in the westward motion of North America in the hotspot reference frame. The end of the Laramide and beginning of widespread arc magmatism and extension correlates with slowing of both of these motions. The spectacular slowing of Farallon-North America convergence is attributed to the decreasing age of the Farallon plate entering the trench and thus to a change from negative to positive buoyancy. The transition from widespread arc-related magmatism and rapid extension to basaltic volcanism and moderate extension in the Basin and Range province finds no ready explanation in the plate motions of the Pacific basin. A change to oblique spreading in the Basin and Range province accompanied growth in length of the San Andreas fault as the Mendocino triple junction progressed northward.

Paper number 3T1886
0278-7407/84/003T-1886$10.00

INTRODUCTION

A model has been developed for the displacement histories between western North America and adjacent oceanic plates (Farallon and Pacific) for the past 145 Ma [Engebretson, 1982]. The model is based on the assumption that the hotspots of the Atlantic region have remained fixed relative to the hotspots of the Pacific basin (L. J. Henderson and R. G. Gordon, personal communication, 1981) and uses a new determination of the relative motions between the Pacific and Farallon plates. Here we examine the implications of this plate model for tectonic processes, focusing on a particular latitude band, the northern Basin and Range province, and the northern region of Laramide thrusting and uplift in the western United States. We recognize that plate motions and plate ages are different at other latitudes. Our objective in the present paper is to determine whether, at one latitude, Pacific basin plate motions can be correlated with tectonic and magmatic events more than 1000 km into the continental interior.

Figure 1 summarizes many of the results from the plate motion model. The upper curve is the component of motion of the Farallon plate with respect to North America, in a direction perpendicular to an assumed coastline trend of N40°W. Note the great range in convergence velocity, which varies in Figure 1 from about 10 to

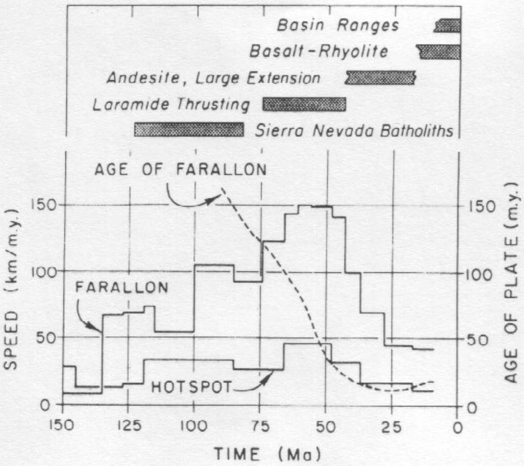

Fig. 1. Components of the Farallon Plate motion relative to North America and of North America over the hotspots, perpendicular to an assumed coastline trend of N40°W near present day San Francisco. The dashed curve is the approximate age of the Farallon plate that was being subducted near the latitude of San Francisco. Bar graphs at the top indicate time spans of major tectonic and magmatic events on the continent. "Andesite" includes andesitic volcanism and the ignimbrite flare up in Nevada and Utah.

150 km/Ma. The lower curve shows the component of motion of North America with respect to the hotspots in a direction normal to the coastline. Although the range of speeds is not as great as that of the Farallon plate, these velocities vary by a factor of 4. The dashed curve shows the age of the Farallon plate that was being subducted at various times. The three curves in Figure 1 apply to the latitude and longitude of San Francisco. Note the general decrease in age of the Farallon plate being subducted as the Pacific-Farallon ridge approached the trench. The curves terminate at about 8 Ma, which approximately marks the passage of the Mendocino Triple Junction and the juxtaposition of the Pacific plate against North America at this location.

EVENTS ON THE CONTINENT

Although the tectonic history on the continent is complex and only partly understood, events during this time were dramatic (bar graphs, Figure 1): (1) The emplacement of batholiths in the Sierra Nevada stopped at about 80 Ma [Chen and Moore, 1982], ending a long period of arc magmatism associated with a steeply subducting slab. (2) Laramide compressional deformation extended far to the eastward --to Wyoming, Utah, and Colorado (and to the south as far as New Mexico and Texas)-- and had little associated magmatism, especially in the northern part. This period has been called the Paleogene magmatic null [Dickinson and Snyder, 1978]. Evidently the subducting slab had flattened abruptly (or a new flat slab had formed) and had coupled with the overlying continental lithosphere [Lipman et al. 1971; Dickinson and Snyder, 1978]. Why did this happen? The most dramatic change in plate motions at this time was the increased rate of Farallon-North America convergence, but there was also a modest speed-up of North America relative to the hot spots at about this time. Presumably, this was accompanied by the westward movement of North America toward and over the adjacent descending slab, assuming that broadside motion of the subducted slab in the hotspot reference frame was slow. Figure 2 shows the track of a point near present-day San Francisco (S) riding with North America in the hotspot reference frame. The present coastline of North America is shown at the left and earlier positions of the coast are shown at intervals of 10 million years back to 180 Ma. The approximate time span of Laramide compression is indicated by shading. Note that there is a speed-up perpendicular to the coastline near the start of Laramide and a marked slowdown near the end (see Figure 1).

We think that the flattening of the plate and the beginning of Laramide thrusting (Figure 1) may have required a coincidence of (1) increased North America velocity toward and over the subducted plate and (2) rapid convergence of the Farallon plate toward North America. Note that although the plate entering the trench was getting progressively younger and hence more buoyant during the Laramide, it was still more than 100 million years old at the beginning of the Laramide.

The third major event (Figure 1) was the ending of Laramide compression and the nearly coincident beginning of widespread arc-related magmatism, which in the northern Basin and Range province started with andesites and continued with the "ignimbrite flare up" [see Stewart and Carlson, 1976, for maps of the igneous rocks in

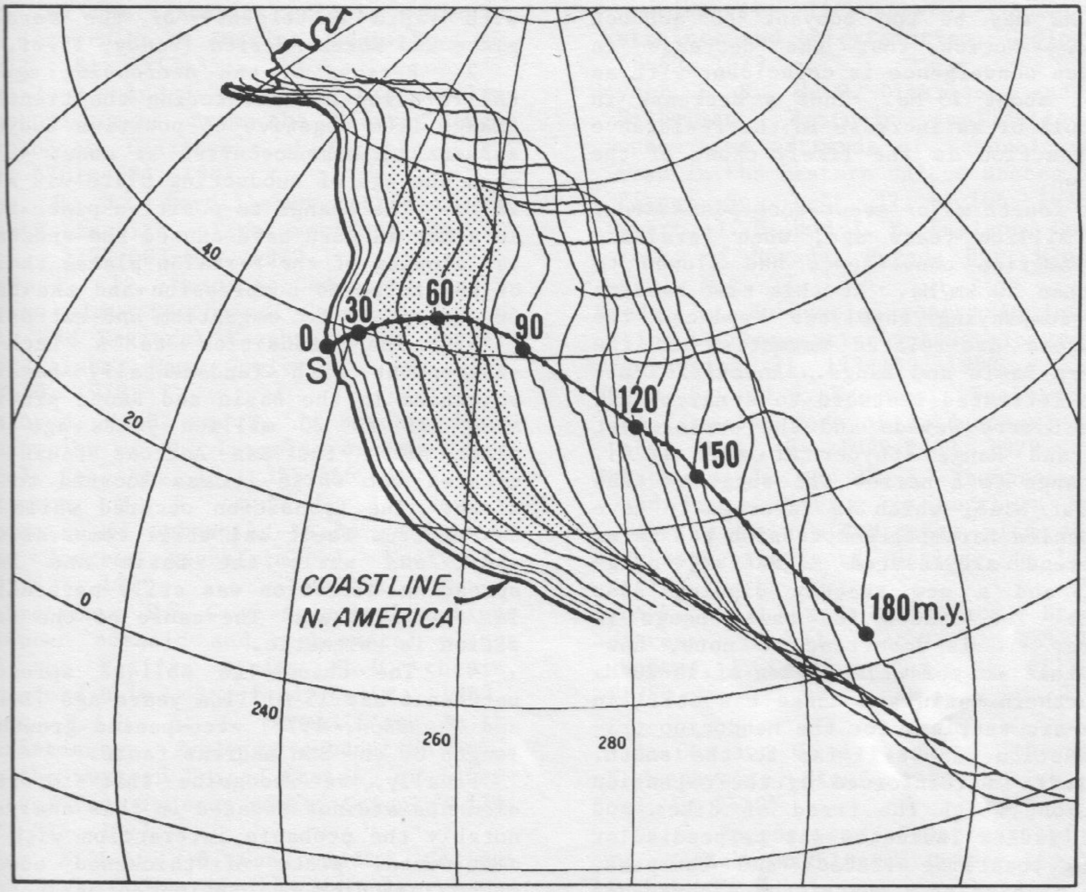

Fig. 2. Motion of North America with respect to the hotspots for the past 180 Ma in 10-m.y. intervals. The dark line with closed circles is the trajectory of a point riding with North America near present-day San Francisco (S) at 5 m.y. intervals with the larger closed circles at 30 m.y. intervals. Shaded region indicates time span of Laramide orogeny.

various time windows]. This was also a period of the intense extension recorded in the metamorphic core complexes [Coney, 1978; Armstrong, 1982; Miller et al., 1983]. It is worth emphasizing that this intense extension took place while subduction was still going on all along the coast and therefore prior to the formation of a slab window [Dickinson and Snyder, 1979]. These pre-Miocene extensional events, which are older than the block faulting that outlined the present basins and ranges, are associated with andesitic magmatism and may be compared with intra-arc spreading in the Marianas Arc.

What brought about the abrupt change from Laramide compression to extension accompanied by a flare-up of magmatic activity? Presumably it reflects the transition from strong to weak coupling between the converging plates, possible causes of which have been reviewed by Uyeda [1982]. In our model the obvious correlation is with a combined slowdown in Farallon-North America convergence and an almost simultaneous slowdown of North America over the hotspots. Although we do not see actual retreat of the North American plate from the trench line, the mechanism favored by Uyeda, with slower convergence and lower compressive stress, magmas could rise more easily through the crust, and perhaps stored heat could be rapidly released.

The kinematic model also provides a strong clue as to why the Farallon plate slowed. At the trench the subducting plate was steadily becoming younger and more buoyant. Molnar and Gray [1979] suggest that oceanic plate younger than about

50-30 Ma may be too buoyant to subduct easily. Notice that the decrease in Farallon convergence is coincident with an age of about 25 Ma. Thus a decrease in slab-pull or an increase in the resistance to subduction is the likely cause of the slowdown.

The fourth major event took place about 15-20 million years ago, when Farallon-North America convergence had slowed to less than 50 km/Ma. At this time basalts and accompanying rhyolites replaced the widespread arc-related magmatism in the northern Basin and Range. Andesitic volcanism retreated westward to a narrow arc in the Sierra Nevada and the westernmost Basin and Range [Snyder et al., 1976]. The change to a narrow arc suggests that the flat slab, which is inferred to have accompanied Laramide compression and later widespread arc-related magmatism, stagnated, and a new steeply dipping slab formed. The reason for this change is obscure. It is important to note, however, that in this time frame of 15-20 Ma the northern Basin and Range was still in a back-arc setting, for the Mendocino triple junction was still far to the south. This fact is reinforced by the extension direction, which the trend of dikes and normal faults indicates was perpendicular to the coastline [Zoback and Thompson, 1978]; no hint of a superimposed shear and oblique opening [Atwater, 1970] was yet evident.

Today this region is inboard of a transform boundary and may overlie a "no-slab window" [Dickinson and Snyder, 1979] or stagnant fragments of a plate, but Basin-Range block faulting and associated basaltic volcanism continue to be active. Thermal and convective processes set in motion in an arc and back-arc environment are still going on, but because of the progressive coupling of the San Andreas transform the opening direction has changed from perpendicular to the coastline to oblique west-northwest extension [Atwater, 1970; Zoback and Zoback, 1980].

SUMMARY AND CONCLUSIONS

1. For the Laramide compressional deformation, plate motions do not support a simple model of the subducting plate being very young and buoyant. They lend some support to the anchored slab model [Uyeda and Kanamori, 1979] of rapid continent motion over the subducted slab. However, the most striking correlation is with rapid convergence of the Farallon plate and North America [Coney, 1978].

2. Because of the decreasing age of the Farallon plate entering the trench, a change from negative to positive buoyancy appears to have occurred at about 40 Ma, when the age of subducting plate was about 25 Ma. The change to positive plate buoyancy may in turn have caused the spectacular slowing of the Farallon plate, the end of the Laramide compression and the onset of widespread arc magmatism and extension.

3. The transition to a back-arc environment with fundamentally basaltic volcanism in the Basin and Range province about 15 to 20 million years ago took place after the San Andreas fault was created but while it was located to the south. The transition occured while the San Andreas fault was still comparatively short and while the Basin and Range spreading direction was still perpendicular to the coast. The cause of the transition is enigmatic.

4. The change to oblique spreading between 6 and 15 million years ago [Zoback and Thompson, 1978] accompanied growth in length of the San Andreas fault.

Finally, we recognize that important elements are not treated in this analysis, notably the probable interaction with the continental plate of thickened oceanic crust including the freight of allochthonous terranes carried on the plates. We have also not treated the north-south variations in the age and thickness of the Farallon plate, which are abrupt across transform faults and may have influenced tectonic and magmatic events on the continent. Also the effects of the interaction of the Kula plate to the north of the Farallon and the resultant Kula-Farallon-North America triple junction need to be considered in a more complete analysis.

Acknowledgments. We especially thank Ben Page for in-depth discussion of the tectonics and we thank other colleagues too numerous to mention. The research was supported by National Science Foundation grants EAR78-22762, EAR79-19712 and EAR81-07702.

REFERENCES

Armstrong, R. L., Cordilleran metamorphic core complexes - from Arizona to Southern Canada, Ann. Rev. Earth Planet. Sci., 10, 129-154, 1982.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, Geol. Soc. Am. Bull., 81, 3513-3536, 1970.

Chen, J. H., and J. G. Moore, Uranium-lead isotopic ages from the Sierra Nevada batholith, California, J. Geophys. Res., 87, 4761-4784, 1982.

Coney, P. J., Cordilleran tectonics and North America plate motions, Am. J. Sci., 272, 603-628, 1972.

Coney, P. J., Mesozoic-Cenozoic Cordilleran plate tectonics, Cenozoic Tectonics and Regional Geophysics of Western Cordillera, Mem. Geol. Soc. Am., 152, 33-50, 1978.

Dickinson, W. R. and W. J. Snyder, Plate tectonics of the Laramide orogeny, Mem. Geol. Soc. Am., 151, 355-366, 1972.

Dickinson, W. R. and W. J. Snyder, Geometry of subducted slabs related to San Andreas transform, J. Geol. 87, 609-627, 1979.

Engebretson, D. C., Relative motions between oceanic and continental plates of the Pacific Basin, Ph.D. thesis, Stanford Univ., Stanford, Calif., 1982.

Lipman, P. W., H. J. Proska, and R. L. Christiansen, Evolving subduction zones in the western United States, as interpreted from igneous rocks, Science, 174, 821-825, 1971.

Miller, E. L., P. B. Gans, and J. Garing, The Snake Range decollement: An exhumed mid-Tertiary ductile-brittle transition, Tectonics, 1, 239-263, 1983.

Molnar, P., and D. Gray, Subduction of continental lithosphere; Some constraints and uncertainties, Geology, 7, 58-62, 1979.

Snyder, W. S., W. R. Dickinson, and M. L. Silberman, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States, Earth Planet. Sci. Lett. 32, 91-106, 1976.

Stewart, J. H. and J. E. Carlson, Cenozoic rocks of Nevada, Nevada Bur. Mines and Geol. Map, 52, 1976.

Uyeda, S., Subduction zones: An introduction to comparative subductology, Tectonophysics, 81, 133-159, 1982.

Uyeda, S. and H. Kanamori, Back-arc opening and the mode of subduction, J. Geophys. Res., 84, 1049-1062, 1979.

Zoback, M. L. and G. A. Thompson, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets, Geology, 6, 111-116, 1978.

Zoback, M .L. and M. Zoback, State of stress in the conterminous United States, J. Geophys. Res., 85, 6113-6156, 1980.

A. Cox and G. A. Thompson, Department of Geophysics, Stanford University, Stanford, CA 94305

D. C. Engebretson, Department of Geology, Western Washington University, Bellingham, WA 98225.

(Received February 28, 1983;
accepted June 20, 1983.)