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THE SUBDUCTION OF THE FARALLON PLATE BENEATH NORTH AMERICA AS DERIVED FROM RELATIVE PLATE MOTIONS

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Abstract. High rates of subduction and near normal convergence of the Farallon plate correlate with the duration of the Laramide Orogeny in the Western Cordillera. The motion of the Farallon plate relative to North America is reconstructed back to the late Mesozoic using relative plate motion data. This reconstruction involves the use of a plate circuit in which each plate is linked to another with seafloor spreading information in order to relate converging plates. Two models for relative motions are considered. The preferred model predicts an increase in the subduction rate of the Farallon plate, exceeding 150 mm/yr, with a direction almost due east and perpendicular to the continental margin. The duration of this nonoblique (normal), high-rate subduction correlates well with the duration of the Laramide Orogeny. This correlation must be regarded as only suggestive; the probable errors, when combined and propagated through the relative motion circuit, may be of the order of the effect observed. However, it is encouraging that these reconstructed Farallon/North American relative motions are similar to the published predictions of others, using the alternative, more direct approach of hot spot reconstructions.

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INTRODUCTION

It has long been suspected that the major Cenozoic deformation of the western Cordillera is somehow related to the large scale plate interactions at the continental margin [Atwater, 1970; Coney, 1978]. A knowledge of the history of subduction along the western margin of North America during the Cenozoic and late Mesozoic is important in the evaluation of this possibility. For this evaluation, the relative motion of the Farallon and North American plates was reconstructed for the last 80 m.y. The approach taken is unfortunately, but necessarily, an indirect one: a plate circuit, where two plates separated by a ridge are related to each other by using seafloor spreading data, and additional plates are similarly tied into the circuit in order to link the Farallon and North American plates. An alternative approach, more direct but involving its own assumptions, is the use of hot spots. In this, dated hot spot tracks are first used to find the "absolute" motions of the Pacific and North American plates. The seafloor spreading history between the Pacific and Farallon plates is used to find the absolute motion of the Farallon plate, and then the relative motion of pairs is found. Comparison of the results of these two approaches may give an indication of the validity of the assumptions involved in each approach. Since the first attempt to relate the Pacific plate to North America for the last 38 m.y. using a plate circuit [Atwater and Molnar, 1973], there has been considerable expansion, refinement, and reinterpretation of the relevant seafloor spreading data. Therefore, an attempt is made here to extend this approach back to the Late Cretaceous to determine the subduction history of the Farallon plate and relate it to the major tectonic events in the North American Cordillera. A major problem in using a plate motion circuit is the possible existence of an additional plate boundary in the circuit, either in the Pacific plate (both an east-west and a north-south boundary have been proposed) or in the Antarctic plate. In this paper an updated determination of the motion of the Farallon plate relative to North America is made for two alternative models. The predicted rates and direction of Farallon subduction for these models are compared with the results of paleomagnetic and geological studies of the Cordillera to determine if first-order changes in plate motions are related to major tectonic events on land. The errors that are associated with the two alternative models must be estimated to evaluate if the first-order changes in plate motions are significant and related to major tectonic events on land.

RELATIVE PLATE MOTIONS

In the plate tectonic framework the motion of the subducted Farallon plate cannot be directly related to North America. In order to reconstruct the motion of a subducting plate to an overriding one, it is necessary to follow through a circuit of relative motions. Each link in the circuit is seafloor spreading data relating two plates that are separated by a ridge. The circuit for the reconstruction of the Farallon plate (FAR) to the North American plate (NAM) is shown in Figure 1. This approach was first taken by Atwater and Molnar [1973] to determine the motion of the Pacific plate relative to North America in order to compare geologic offsets along the San Andreas fault to Atwater's [1970] inferences from magnetic anomaly orientations. In the last decade there has been considerable expansion, refinement, and reevaluation of the seafloor spreading data set. For the reconstructions in this study, the Farallon plate is related to the Pacific with the rotation parameters of W. J. Morgan (personal communication, as shown by Scientific Staff [1978, Figure 1] for the last 30 m.y. and with the rotation poles of Francheteau et al. [1970] and the rates estimated by Carlson [1982] for earlier times; the Pacific plate is related to Antarctica (West) by using the data of Weissel et al. [1977]; Antarctica (East) is tied to Africa according to Norton and Sclater [1979], and the circuit is completed with Africa tied to North America by using the determinations of Pitman and Talwani [1972]. The magnetic polarity scale of Harland et al. [1982] is used to date magnetic anomalies.

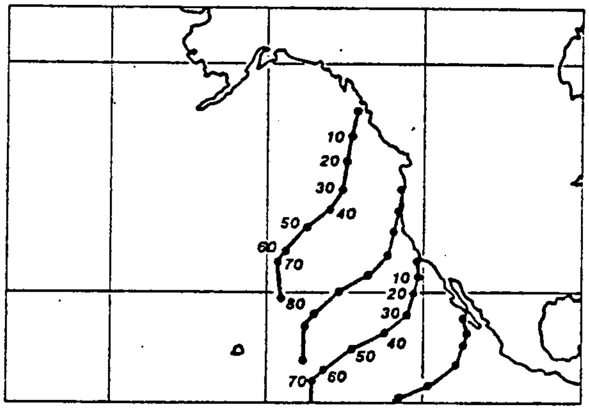
Relative Plate Motion Circuit

FAR - PAC (N?S or E?W) - ANT (E?W) - IND - AFR - NAM

Fig. 1. Circuit of relative plate motions to relate the subducting oceanic Farallon plate to the overriding continental North American plate. FAR, Farallon; PAC, Pacific (north and south or east and west); ANT, Antarctica (east and west); IND, Indian; AFR, African; NAM, North American.

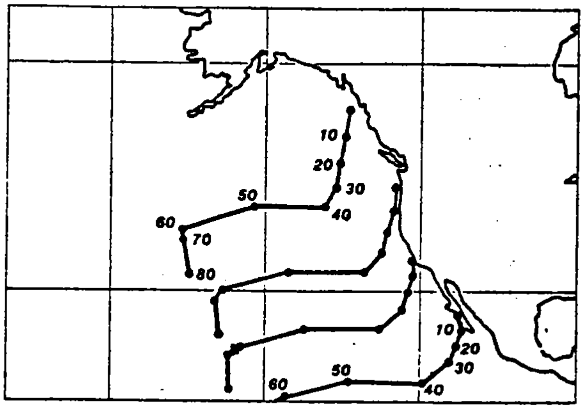
There is a strong possibility of an additional plate boundary in this circuit [Jurdy, 1978, 1979; Gordon and Cox, 1980]. A number of possibilities have been suggested. Farrar and Dixon [1981] propose a northeast-southwest trending boundary in the Pacific plate along the Emperor fracture zone system active during the early Tertiary. However, Gordon [1982] paleomagnetically tests this hypothesis and rejects it. An east-west boundary, just northeast of the Chatham Rise, is proposed by Gordon and Cox [1980] as splitting the Pacific plate. However, Cande et al. [1982] consider magnetic anomalies and conclude that a plate boundary is not likely in this region either. The integrity of the Antarctic plate has also been called into question [Dalziel, 1982; Jurdy, 1978, 1979; Molnar et al., 1975; Stock and Molnar, 1982]. For this reason, an alternative model for the relative plate motions was considered with relative motion between East and West Antarctica as modeled by Stock and Molnar [1982].

Hot spots provide a more direct, alternative approach to determining the subduction history of the Farallon plate. In this approach, dated hot spot tracks are used to find the "absolute" motion of each individual plate; the difference between these absolute motions is then the relative motion [Morgan, 1981]. However, because North America has few hot spots, it is necessary to use seafloor spreading data to relate North America to Africa and then to determine Africa's absolute motion relative to its more numerous hot spots. A similar approach is necessary for the Farallon plate, which has largely been consumed: its motion relative to the Pacific plate is inferred from magnetic anomalies and fracture zones remaining on the Pacific plate [Engebretson, 1982]. The Pacific plate's absolute motion is then determined by using its hot spot tracks. Although the approach of using hot spots to reconstruct the relative motion of the Farallon and North American plates makes use of limited relative motion data, it does avoid the difficulties caused by the possibility of an additional plate boundary in the Pacific or Antarctic (or perhaps both!) plates. The underlying assumption, however, is that the hot spots are a rigid framework. Comparison of the results of the two approaches, one based on hot spots and the other on a relative motion circuit, may help us to evaluate the validity of our assumptions and the size of the errors involved in the determinations.


FARALLON TO NORTH AMERICA

Antarctica one plate

Fig. 2. Trajectory at 10-m.y. intervals of four sample points on the Farallon plate relative to North America which is assumed fixed. The point at the coast was at location 10, 10 m.y. B.P., at 20, 20 m.y. B.P., etc. Antarctica is assumed to be a single plate (Mercator projection).


FARALLON TO NORTH AMERICA

Antarctica two plates

Fig. 3. Trajectory at 10-m.y. intervals of four sample points on the Farallon plate relative to North America which is assumed fixed. The point at the coast was at location 10, 10 m.y. B.P., at 20, 20 m.y. B.P., etc. Antarctica is treated as two plates as modeled by Stock and Molnar [1982] (Mercator projection).

SUBDUCTION HISTORY OF THE FARALLON PLATE

The motion of the Farallon plate relative to North America is found by using a relative plate motion circuit (Figure 1) with the published seafloor spreading data described in the previous section. North America is held fixed. The results are shown in Figure 2 for the case of no additional plate boundary in the circuit. The motion is almost due north from 80 to 70 m.y. B.P., north-north-east from about 70 to 30 m.y. B.P. and almost due north again from 30 m.y. B.P. to the present. The results are significantly different (Figure 3), however, if Antarctica is treated as two converging plates, as modeled by Stock and Molnar [1982]. For this case, the subduction direction of the Farallon plate is almost due east for the period from 60 to 40 m.y. B.P. and at a very high rate. This is a direct consequence of the joining of East and West Antarctica over this time period; none of the other relative motions of plate pairs are changed.

A breakdown into components of the convergence shown in Figures 2 and 3 is useful for a comparison of the results of the two models of relative motions. In Figure 4 the amount of convergence and its components in directions tangential (oblique)

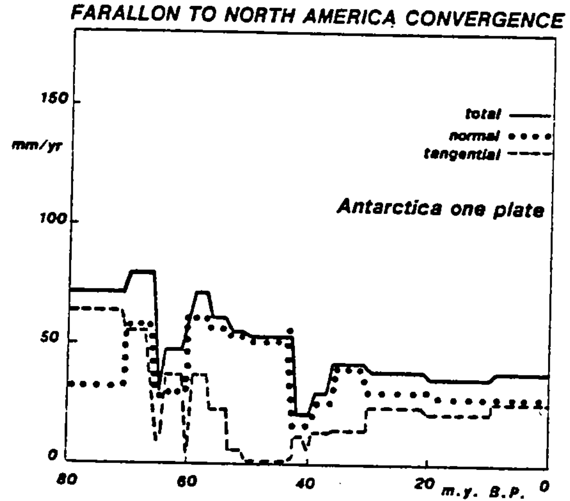


Fig. 4. Decomposition of the convergence (Figure 2) of the Farallon plate relative to North America into components normal and tangential to the coast for the last 80 m.y. Antarctica is assumed to be a single plate.

and normal (perpendicular) to the North American coast are shown for the last 80 m.y. for the results of the single Antarctica model shown in Figure 2. A similar decomposition is shown in Figure 5 for the subduction history of the two Antarctica plate model. For purposes of computation, the coast of North America was represented by the line connecting the northernmost grid point in Figures 2 and 3 to the southernmost one and the convergence vector projected onto this line. Calculations of the two components were made at 1-m.y. intervals by using the stage poles in effect for a specified length of time; the resulting step functions have been joined to define a continuous function of time. In Figures 4 and 5 the absolute value of the tangential component is plotted. The single-plate Antarctica model (Figures 2 and 4) shows total convergence rates of the Farallon plate relative to North America generally in the 40-70 mm/yr range over the last 80 m.y. Neither the normal or tangential component dominates the other, except for a drop almost to zero of the tangential component over the 10 to 15 m.y. period just preceding 40 m.y. B.P. As viewed from the North American plate, this oblique motion is almost entirely right-directed, except for brief (probably insignificant) excursions to the left for a couple of million years. On the other hand, the two-plate Antarctica model (Figures 3 and 5) shows marked variation in the convergence velocities, ranging from a low of 40 mm/yr to a high in excess of 150 mm/yr. As is apparent from Figure 3, the subduction direction changes from right to left just before 60 m.y. ago, and then to the right again at about 40 m.y. B.P. This model, like the previous model, does not show great variation in the relative importance of the normal and tangential components. The most interesting feature, from the point of view of Cordilleran tectonics, is the very high velocities observed from about 60-40 m.y. B.P. This correlates with most of the duration of the Laramide Orogeny, which extended from 75-40 m.y. B.P. [Coney, 1978]. However, the large predicted component of oblique subduction probably could not account for the northward motion of terranes [Coney et al., 1980; Saleeby, 1983]: although it was right-directed from 80 to just before 60 m.y. B.P., the predicted subduction direction then reversed until 40 m.y. B.P. As can be seen by comparing Figures 2 with 3 and 4 with 5, the amount and direction of oblique subduction during the interval from 60 to 40 m.y. B.P. is very sensitive to the assumed relative motion on the additional plate boundary in Antarctica (or in possibly the Pacific plate) during that period. Plate motion models intermediate between these cannot be ruled out. An idealized representation of the total convergence of the Farallon plate with its

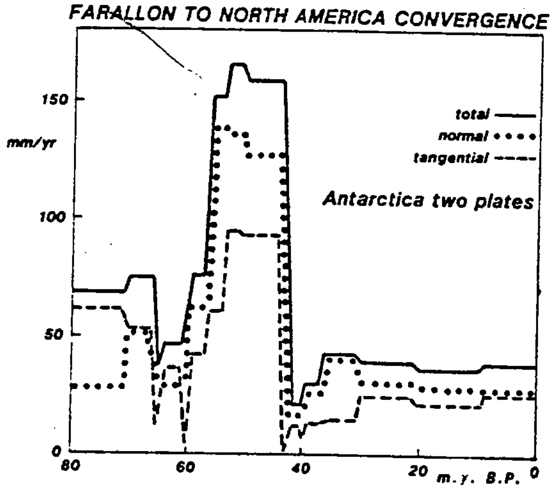


Fig. 5. Decomposition of the convergence (Figure 3) of the (Farallon plate relative to North America into components normal and tangential to the coast for the last 80 m.y. Antarctica is treated as two plates as modeled by Stock and Molnar [1982].

tangential component and the duration of orogeny is shown in Figure 6.

DISCUSSION

The subduction history of the Farallon plate has been reconstructed back to the Late Cretaceous by using a relative plate motion circuit in which the Farallon plate is related to the North American indirectly by using seafloor spreading data from the Pacific, Indian and Atlantic Oceans. This approach was first used by Atwater and Molnar [1973] to relate the Pacific plate to North America for the last 38 m.y. Because of the likelihood that there is an additional plate boundary in this circuit, an alternative model was considered: one in which Antarctica is divided into an east and west portion with relative motion. This preferred, alternative model shows considerable variation in convergence velocity in the last 80 m.y., ranging from 40 to 150 mm/yr. The amounts and directions of convergence established with the relative plate motion circuit for the alternative model are in first order agreement with determinations based on the assumption of fixed hot spots [Coney, 1978; Carlson, 1982; Engebretson et al., this issue], all of which also predict subduction rates in excess of 140 mm/yr during the time interval from 80 to 40 m.y. B.P. There are required assumptions in both approaches. The consumption of the Farallon plate necessitates establishing the Farallon/Pacific relative motion from magnetic anomalies remaining on the Pacific side of the pair and assuming that there has been symmetric spreading. Both approaches require this assumption. In the relative plate motion circuit, used in this paper, the possibility of an additional (unknown) plate boundary in the circuit remains. As can be seen by comparing the results of the two models (Figures 2 and 3, and Figures 4 and 5), moderate motion along an additional plate boundary can significantly influence the final result. The fixed hot spot approach can sidestep this problem of an additional boundary, as long as it does not separate the Pacific or African plates where their hot spots were used for the reconstructions.

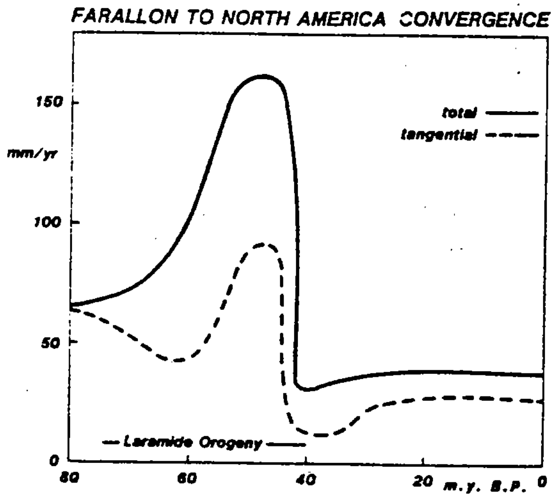


Fig. 6. Schematic representation of the convergence of the Farallon plate relative to North America for the two-plate Antarctica model (Figures 3 and 5) and the extent of the Laramide Orogeny.

A number of simplifications have been made in reconstructing the subduction of the Farallon plate beneath the North American plate. Although only the Farallon plate is shown in Figures 2 and 3, it is most likely that the Pacific and Kula plates were involved in the picture. As discussed by Atwater [1970], the Pacific plate approached North America about 30 m.y. ago. Therefore it is likely that the bottom two grid points were part of the Pacific plate, rather than the Farallon as shown here. Similarly, at earlier times, the Kula plate may have been subducting beneath North America, and thus the northernmost grid point, or perhaps two, may have been the Kula plate in the Late Cretaceous. The location of the Kula/Farallon/North American triple junction with respect to North America is not known with certainty, as discussed by Engebretson [1982]. Late Cenozoic extension in North America may be related to the instability caused by the approach of this triple junction [Ingersoll, 1982]. For simplicity, and the purposes of illustration, all four grid points in Figures 2 and 3 are treated as if they were on the Farallon plate for the entire 80 m.y. of subduction history.

It is now widely accepted that most of the North American Cordillera is composed of suspect terranes that may have originated far from their present location relative to North America [Coney et al., 1980; Saleeby, 1983]. Paleomagnetic studies indicate that there has been considerable northward motion of individual terranes. For example, Cretaceous batholiths in both Washington [Beck et al., 1981] and California [Teissere and Beck, 1973] give pole positions that suggest considerable northward motion, and in the case of the Mount Stuart Batholith in California, the estimated transport rate is greater than 110 mm/yr. Stratigraphic and structural constraints can yield information about the accretion time of a suspect terrane. Studies of two California terranes [McWilliams and Howell, 1982] and the Stikine terrane in British Columbia [Monger and Irving, 1980] suggest that there has been considerable northward transport ending by the middle Tertiary. Similarly, Monger et al. [1982], in a study of Canadian Cordilleran terranes, conclude that the Late Cretaceous or early Tertiary was a time of a major accretionary episode, comparable to that in the Jurassic. Although other interpretations are possible for each of these individual studies and are discussed by the authors, the whole picture emerges of considerable northward transport of Cordilleran suspect terranes [Beck, 1976].

A reasonable inference from this well-documented northward translation of terranes is that the Late Cretaceous to early Tertiary was a time of considerable nonnormal, or oblique, convergence, at rates up to 90 mm/yr. Additional evidence may support the hypothesis that dextral shear occurred along the western margin of North America. On the basis of an analysis of structural elements of the Rocky Mountain region, Hamilton [1981] concludes that Laramide deformation can be modeled as clockwise rotation of the Colorado Plateau with respect to the continental interior during the Late Cretaceous to the early Tertiary.

These paleomagnetic and geological observations require oblique convergence with rates up to 100 mm/yr that to account for the fast northward transport observed. Although the preferred model (Figures 3 and 5) shows a large component of oblique subduction, it is dextral only in the Late Cretaceous and changes to sinistral at the beginning of the Tertiary, and then dextral again at about 40 m.y. B.P. The other model (Figures 2 and 4), also dextral in the Late Cretaceous, has only a very small component of oblique subduction during the early Tertiary. Thus neither model could completely explain the observed large, and possibly very rapid, northward motion of terranes ending in the Tertiary. (Assuming fixed hot spots, Carlson [1982] finds a much greater component of oblique dextral subduction during this time interval, one of 130 mm/yr and about a factor of 3 greater than the normal component that he calculates.) The Kula plate is a promising candidate for the northward transport of terranes, as a major component of its motion was northerly.

The preferred relative motion model, with an additional plate boundary in the circuit, predicts rapid subduction of the Farallon plate beneath North America in the Late Cretaceous and early Tertiary, which correlates with the extent of the Laramide Orogeny. This rapid subduction agrees with the published predictions of others [Coney, 1978; Carlson, 1982, Engebretson et al., 1983] using the alternative, more direct approach of hot spot reconstruction. However, as noted earlier, the hot spot and relative motion circuit approaches are not completely independent; both require seafloor spreading data from the Pacific and Atlantic Oceans. Even so, that the two approaches show similarities in the predicted rates and direction of the subducting Farallon plate is encouraging.

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