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MESOZOIC ASEISMIC RIDGES ON THE FARALLON PLATE AND SOUTHWARD MIGRATION OF SHALLOW SUBDUCTION DURING THE LARAMIDE OROGENY

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Abstract. We propose that an aseismic ridge of Late Jurassic and Early Cretaceous age on the Farallon plate was subducted beneath the Unites States Cordillera during the Laramide orogeny. The relative buoyancy of the aseismic ridge caused shallow subduction which resulted in a magmatic lull 70-40 Ma in the existing near-trench magmatic arc and Laramide uplift and faulting of crystalline basement 1000-1500 km inland from the trench. The timing and latitudinal limits of the subduction of the aseismic ridge are similar to the timing and latitudinal limits of both the Laramide orogeny and the magmatic lull in the western Cordillera. Because the north-northeast trending aseismic ridge was moving northeast relative to the North American plate, the point of collision of the aseismic ridge with North America, and therefore the locus of shallow subduction, migrated southward with time, causing the well-documented southward migration of the magmatic lull.

INTRODUCTION

The Laramide orogeny is unusual in the geologic history of the North American Cordillera in that faulting and uplift of crystalline basement, as well as sporadic magmatism, occurred 1000-1500 km inland from the trench. Prior to 70 Ma the western margin of North America, from British Columbia, Canada, through southeastern California and probably into Sonora, Mexico, was characterized by the formation of imbricate low-angle thrusting and folding of continental shelf and basin strata above little-deformed basement. North of central Utah and south of southeastern California, thrusts with a structural style similar to those developed earlier continued to be formed after 70 Ma, ceasing in mid-late Eocene time (40-45 Ma). Before latest Cretaceous time, thrusting ceased in the thrust belt between central Utah and southeastern California, and structures of a very different tectonic style developed 70-40 Ma in the continental craton in a belt from southern New Mexico to northern Montana. These structures were large uplifts bounded by low- to high-angle reverse faults through crystalline basement rocks with differential vertical displacements up to 10 km [Burchfiel and Davis, 1975; Hamilton, 1978; Coney, 1976, 1978]. During this time interval, magmatism ceased in the arc in corresponding latitudes in the western batholith belt, and sporadic magmatism occurred up to 1500 km from the continental margin [Lipman et al., 1972; Cross and Pilger, 1978; Keith, 1978;

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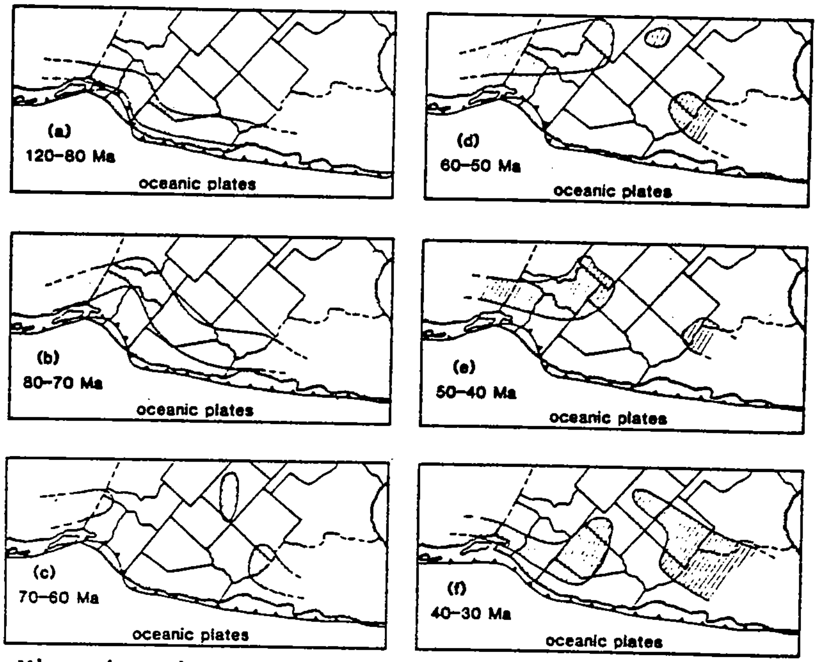

Fig. 1. Migration with time of subduction-related magmatism in the western United States. Striped areas are generalized distributions of andesitic volcanic rocks, believed to be related to subduction. Base map, showing the western United States projected about the present-day rotation pole of the North American plate with respect to the Pacific plate, is from Atwater [1970]. The effects of late Cenozoic extension were not removed. Barbed line shows the inferred trench axis. Modified from Lipman [1980].

Dickinson and Snyder, 1978; Lipman, 1980; Chen and Moore, 1982].

The disruption in subduction-related andesitic magmatism was not synchronous throughout the western arc, but migrated generally southward between 70 and 40 Ma [Lipman, 1980]. Within the limits of the radiometric data, the western magmatic arc appears to have been first disrupted at the latitudes of Oregon and southern Washington by about 65 Ma. By 50 Ma, a lull in magmatism in the western arc extended from Oregon through southern California [Lipman, 1980] (Figure 1). The resumption of magmatism east of the original western batholithic belt began first in Idaho and Montana at 60 Ma, then swept south through Wyoming and Utah to northernmost Nevada by 40 Ma, with sporadic volcanism in Colorado 70-50 Ma. The southern locus of magmatism was confined to southern Arizona and New Mexico between 70 and 40 Ma, then spread through New Mexico and western Colorado by 35 Ma. The southward migration of the disruption of the magmatic arc is best seen in the southward creep of the southern limit of the northern locus of magmatism, which migrated from Washington and Idaho to Nevada and eastern California between 70 and 40 Ma (Figure 1). The relatively narrow Andean-type magmatic arc that had existed along the Cordillera from British Columbia, Canada, through Mexico by Late Cretaceous time was undisrupted in Canada and Mexico [Coney, 1978]. No lull in magmatism occurred adjacent to the portions of the thrust belt where thin-skinned thrust-faulting continued throughout Laramide time [Lipman et al., 1972; Armstrong, 1974; Burchfiel and Davis, 1975].

The magmatic lull and increase in the arc-trench distance during the Laramide orogeny have most often been attributed to the shallow dip of the Farallon lithosphere subducting beneath western North America [Coney, 1972; Burchfiel and Davis, 1975; Coney and Reynolds, 1977; Cross and Pilger, 1978; Dickinson and Snyder, 1978]. This interpretation has been confirmed by analysis of potash contents and inferred paleodepths of the Benioff zone for Cretaceous and Tertiary andesitic rocks [Lipman et al., 1972; Keith, 1978, 1982]. Although several mechanisms have been proposed to account for shallow subduction during the Laramide orogeny, none of these mechanisms account for the well-documented southward migration of inferred shallow subduction. In this paper we propose that the shallowing of subduction and the southward migration of the locus of shallow subduction were caused by the subduction beneath North America of an aseismic ridge riding on the Farallon plate. This model is similar in many important respects to the proposition that the Laramide orogeny was caused by the subduction of an oceanic plateau [Livaccari et al., 1981]. Our model, however, improves on the earlier model by making several detailed predictions that are confirmed by data from the western United States.

In the following sections we first discuss the modern analogs of the elements of our model. We then present reconstructions of the motion of the Farallon plate, the formation of the aseismic ridges on the Farallon plate, and the subduction of these aseismic ridges beneath North America. Finally, we discuss the data that support our model and argue that alternative plate tectonic models for the shallow subduction 70-40 Ma fail to explain all of the observations.

ELEMENTS OF THE MODEL AND THEIR MODERN ANALOGS

Shallow Subduction

We propose that the shallow dip of the subducting slab during the Laramide orogeny was caused by an aseismic ridge or aseismic ridges on the subducting Farallon plate. An aseismic ridge causes shallow subduction because the thick crust associated with the ridge yields a lithospheric column more buoyant than that of normal oceanic lithosphere [Kelleher and McCann, 1976, 1977]. A modern analog occurs where the Nazca plate currently is subducted beneath South America. Aseismic ridges with high relief on relatively old lithosphere are being subducted beneath Chile (Juan Fernandez Ridge) and Peru (Nazca Ridge) (Figure 2). Barazangi and Isacks [1976] have shown that anomalously shallow subduction is occurring in slab segments 500-1000 km long parallel to the trench, adjacent to the points where the aseismic ridges are being subducted. These segments of shallowly dipping slab coincide with regions lacking Quaternary volcanos--major gaps in active volcanism in the Andes.

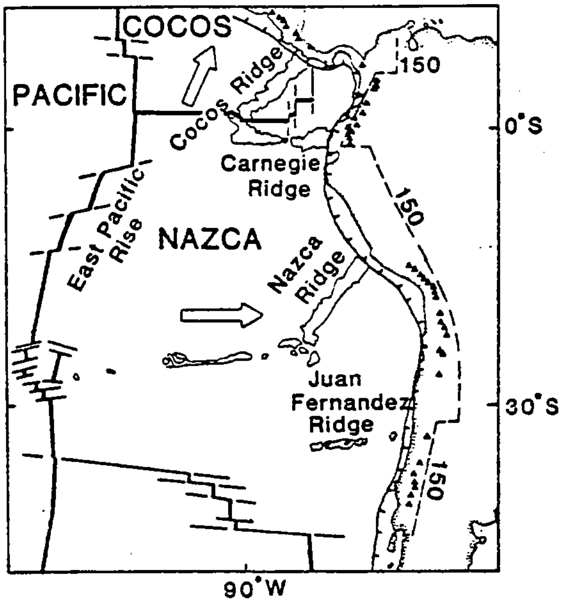

Fig. 2. Major tectonic features of the Cocos, Nazca, and western South American and Caribbean plates. Dashed line labeled "150" shows location of 150-km deep contour of Benioff zone. Arrows show direction of motion of the oceanic plates with respect to fixed South America. Triangles represent zones of active volcanos. Hachured line marks the trench axis. After Isacks and Barazangi [1977].

Figure 2 shows the contour of constant 150 km depth to the Benioff zone beneath South America. The distance of this contour from the trench can be interpreted as showing that normal high-angle subduction is occurring south of the collision point of the Nazca Ridge. North of the locus of collision, where plate reconstructions show that the northeast continuation of the Nazca Ridge has recently been subducted [Pilger, 1981; Nur and Ben-Avraham, 1981], the slab is descending at an unusually shallow angle. Moreover, south of the collision point, there is normal subduction-related volcanism (the active volcanos being indicated by triangles in Figure 2), whereas north of the collision point there is a gap in subduction-related volcanism. Neither variations in the age of the Nazca plate nor variations in net convergence velocity along the Peru-Chile trench can explain the locations of the shallowly dipping segments [Pilger, 1981].

Migration of Shallow Subduction

As proposed here, the region of shallow subduction migrated to the south with time during the Laramide orogeny because the Farallon plate was moving northeast relative to North America, and the subducting aseismic ridge trended north-northeast. Thus the first point on the ridge to be subducted at the roughly north-northwest striking trench was the northern tip of the ridge. As the Farallon plate continued to move northeastward, points farther southwest along the ridge contacted the trench, causing the point of collision and the inferred transition between high- and low-angle subduction to migrate southward with time (Figures 3b-3f).

The southward migration of the locus of shallow subduction during the Laramide orogeny is analogous to the southward migration of the point of collision of the Nazca Ridge and the Peru-Chile trench during the last few million years and the resultant southward migration of the magmatic gap. Pilger [1981] and Nur and Ben-Avraham [1981] have argued that the recently subducted portion of the Nazca Ridge strikes to the northeast, parallel to the observed portion of the Nazca Ridge on the Nazca plate. Thus, because the Nazca plate moves east relative to South America and because the trench along Peru strikes northwest-southeast, the point of collision has migrated southward with time. This leads to the inference that the boundary between high-angle (normal) subduction (and accompanying subduction-related volcanism) and low-angle (anomalous) subduction may also have migrated southward, following the point of collision.

Aseismic Ridges on the Farallon Plate

Because most of the Farallon plate has been subducted, we can never know with absolute certainty where aseismic ridges were located on the Farallon plate. However, this does not mean we have no information regarding their location. On the contrary, we know that many of the major volcanic edifices of the Pacific plate were formed at or very near the ancient Pacific-Farallon ridge crest [Hilde et al., 1976; Watts et al., 1980]. In analogy with hot spots currently located at ridge crests--such as the Galapagos hot spot, which has created the Cocos and Carnegie Ridges (Figure 2), and the Iceland hot spot, which has created the Iceland and Faeroe Ridges--we can reasonably assume that any Pacific plate volcanic edifices that may have formed at or very near the ridge crest had counterparts on the Farallon plate [Livaccari et al., 1981]. By knowing the age and geometry of the hot spot track formed on the Pacific plate [Henderson and Gordon, 1981] and by knowing the relative motion between the Farallon plate and Pacific plate [Engebretson et al., 1984], we can model the age and geometry of the proposed Farallon volcanic edifices formed at the spreading ridge.

There is considerable evidence that many major Pacific plate volcanic edifices (Shatsky Rise, Manihiki Plateau, Magellan Rise, and portions of Hess Rise, the Mid-Pacific Mountains, and the Line Islands) were formed at or very near the ridge crest [Hilde et al., 1976; Watts et al., 1980]. Therefore each of these plateaus probably had counterparts on the Farallon plate. For the purposes of the present model, we limit our attention to the Farallon plate counterparts of the Shatsky Rise and Hess Rise.

RECONSTRUCTIONS

Components of the Model

Our reconstructions consist of two elements, the displacement history of the Farallon plate with respect to western North America and the locations of the aseismic ridges on the Farallon plate. The first element, the displacement history of the Farallon plate with respect to western North America, is based on the assumption that the hot spots in the Pacific and Atlantic regions have remained fixed or moved only very slowly with respect to one another, an approach first applied by Morgan [1972] to the analysis of plate motions and first applied by Coney [1972, 1978] to the analysis of the convergence history and tectonic evolution of western North America during the Mesozoic and Cenozoic. The rotations of the Farallon plate with respect to North America were determined by combining together the rotations of North America with respect to the hot spots, the rotations of the Pacific plate with

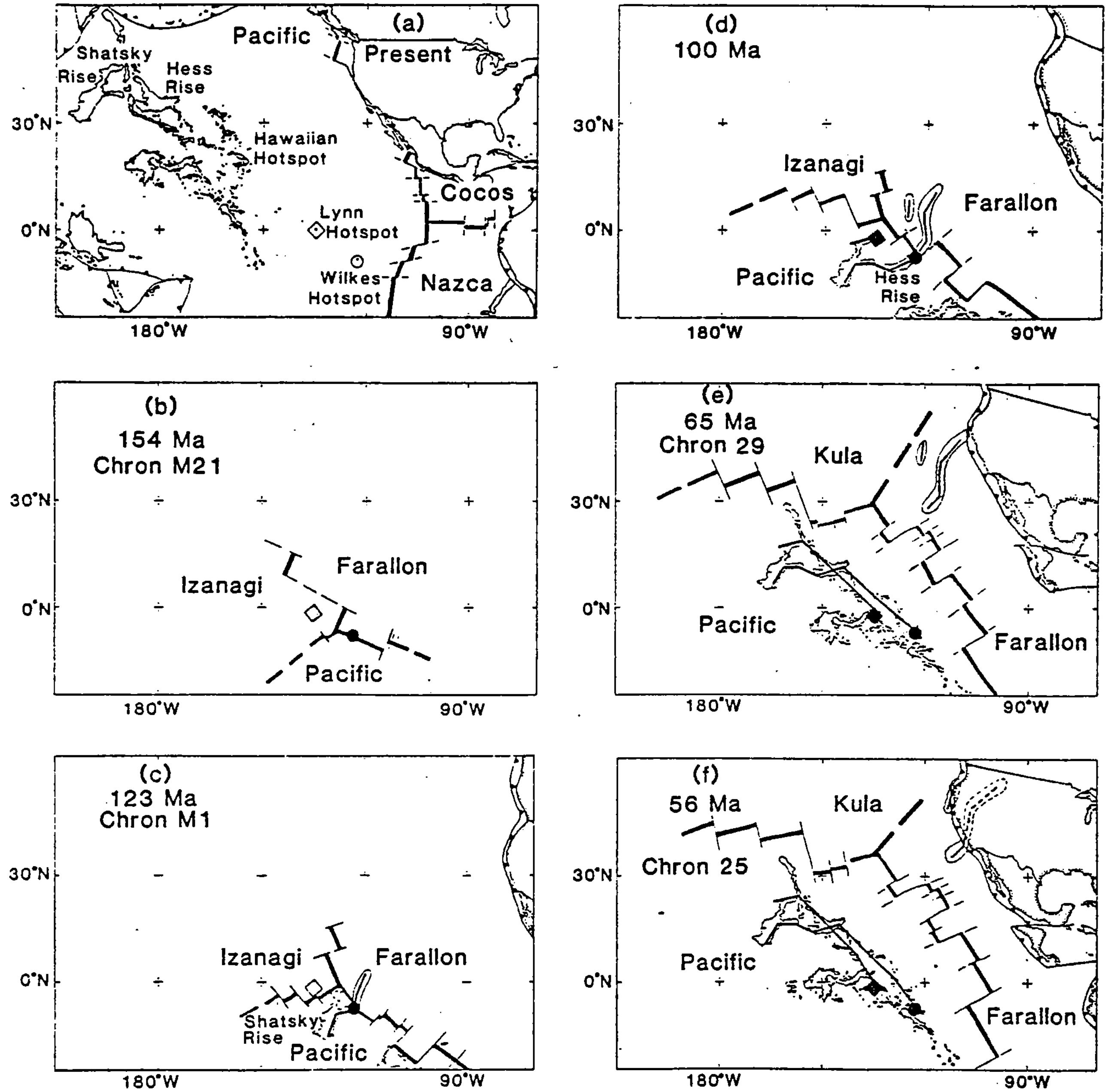

Fig. 3. Reconstructions of the lithospheric plates with respect to the hot spots, and formation of hot spot-produced volcanic edifices on the Pacific and Farallon plates at the spreading ridge. Hot spots are held fixed and the oceanic and continental plates are moved with respect to the hot spots from 154 Ma to 56 Ma. Large symbols show locations of the active hot spots in each frame, heavy lines show the tracks left on the oceanic plates by their motion over the hot spots. The large symbols are solid when the hot spots were located on the Pacific plate and open when the hot spots were located on the Kula plate. (a) The present location of the Lynn Seamount hot spot, the Wilkes hot spot, and the Hawaiian hot spot on the Pacific plate. (b)-(f) Reconstructions of plates, continents, and aseismic ridges. Locations of aseismic ridges shown subducted beneath North America are uncorrected for the dip of the slab. Barbed line marks the trench axis. Very heavy lines mark the ridge axes. This is a Mercator projection.

TABLE 1. Pacific-Hot Spot Stage Poles

From	To	Pole Latitude, °N	Pole Longitude, °E	Angle	Reference
25	0	70.0	265.0	24.0	Turner et al. [1980]
43	25	70.0	265.0	11.0	Turner et al. [1980]
75	43	17.0	253.0	20.0	Clague and Jarrard [1973]
100	75	36.0	284.0	24.0	Epp [1978]
115	100	81.7	100.4	9.8	this paper
123	115	60.0	280.2	6.0	this paper
132	123	36.7	344.1	4.9	this paper
154	132	32.5	61.2	7.0	this paper

The poles are in a reference frame fixed with respect to the Pacific plate. When rotating the Pacific plate relative to the hot spots from the younger time to the older time, a positive sign corresponds to a right-handed rotation (counterclockwise to an observer looking down on the earth).

respect to the hot spots, and the rotations of the Farallon plate with respect to the Pacific plate. We adopted the rotations of North America with respect to the hot spots of Morgan [1983], but we have adjusted the ages of his reconstructions to be consistent with the magnetic reversal time scale of Harland et al. [1982], which is used throughout this paper. The rotations of the Farallon plate with respect to the Pacific plate are from Engebretson et al. [1984]. The rotations we used for the motion of the Pacific plate with respect to the hot spots (Table 1) are based on reconstructions of Henderson and Gordon [1981]. These Pacific-hot spot rotations are more detailed than those of Morgan [1972], but the general pattern of motion over the last 150 m.y. is similar for the two sets of rotations: relatively slow westward motion 150-100 Ma, relatively rapid northwestward motion 100-40 Ma, and relatively rapid west-northwestward motion 40 Ma to present.

From these rotations we obtain not only the motion of the Farallon plate with respect to North America, but the motion of the Farallon plate with respect to the hot spots, from which the trend of any seamount chains or aseismic ridges produced by hot spots on the Farallon plate is determined. We emphasize that for any volcanic lineament (seamount chain or aseismic ridge) produced on the Farallon plate by a hot spot during Late Jurassic and Early Cretaceous time, the trend of the lineament depends strongly on the Farallon-hot spot motion and only weakly on the location of the hot spot. This is important because it is the north-northeast trend of the aseismic ridge, combined with the northeast displacement during the Late Cretaceous and early Tertiary of the Farallon plate with respect to North America, that causes a north-to-south migration of the point of collision of the aseismic ridge with the western plate margin of North America.

The precise locations of the hot spot tracks on the Farallon plate depend on the locations we assume for the hot spots that created the tracks. Based on interpretations of other hot spots and their Cenozoic tracks, no hot spot with a clear Cenozoic track could have made the Shatsky Rise and Hess Rise. Therefore neither the current locations nor the Cenozoic tracks of the hot spots that created Hess Rise and Shatsky Rise have yet been recognized. Figure 3a shows where these hot spots, which we call the Wilkes hot spot and the Lynn hot spot, would now be if they are still active, if our reconstructions from 100 Ma to the present are accurate, and if our assumed correlations between points along Hess Rise and other Pacific volcanic features are correct. The interpretation of the Cenozoic tracks of these hot spots is beyond the scope of the present paper and will be discussed in detail elsewhere (L. J. Henderson and R. G. Gordon, manuscript in preparation, 1984).

In Figures 3b-3f, we have reconstructed the location of the Pacific plate with respect to the hot spots and have shown the tracks of the Lynn and Wilkes hot spots as the tracks were created on the Pacific plate. We have shown no tracks of hot spots that would have formed on the Kula plate, and no tracks that would have formed on the Farallon plate but had no counterpart on the Pacific plate (e.g., the Yellowstone hot spot, which may have been active during the Cretaceous and, if active, would have been located beneath the Farallon plate). Instead, the tracks of the Wilkes and Lynn hot spots are modeled on the Farallon plate only if the ancient Farallon-Pacific spreading center lay above or nearly above (within 250 km) either of these hot spots, in which case we have assumed that volcanic edifices formed on both the Pacific plate and the Farallon plate. It is not critical to our model that the Farallon-Pacific spreading center always lay precisely above these hot spots if, as Morgan [1978, 1981] and Vink [1982] have argued, the proximity of a hot spot to a spreading center results in the channeling of asthenosphere to the section of the spreading ridge closest to the hot spot. However, the available data do not preclude the Pacific-Farallon ridge crest having been directly above the Wilkes hot spot continuously from 154 to 100 Ma.

The first of a time sequence of reconstructions was made for 154 Ma (chron M21), the age of the oldest seafloor beneath Shatsky Rise (Figure 3b). Before 154 Ma the Wilkes and Lynn hot spots may have been active and located exclusively beneath the Farallon plate or Kula plate, but there is no evidence from the seafloor that could confirm or deny this hypothesis. At 154 Ma, the Wilkes hot spot was located at the Pacific-Farallon ridge crest, at the western edge of what is now the Shatsky Rise. The Lynn hot spot, if it was active at 154 Ma, was located beneath the Kula plate and thus made no track on the Pacific or Farallon plates at that time.

The major part of the Shatsky Rise and its counterpart on the Farallon plate had formed by 123 Ma as the Pacific plate moved southwestward and the Farallon plate moved northeastward between 154 and 123 Ma (Figure 3c). By 100 Ma the Mellish Bank, the west-southwest trending aseismic ridge that comprises most of the southern portion of the Hess Rise, had been produced by the Wilkes hot spot (Figure 3d). As can be seen in Figures 3c and 3d, our interpretation is that Wilkes hot spot produced most of Shatsky Rise and Hess Rise, the continuity of these rises having been subsequently obscured by the formation of the Emperor Seamount chain. In our model the Farallon plate counterpart of Shatsky Rise and Hess Rise that was produced by the Wilkes hot spot is a north-northeast trending aseismic ridge (Figure 3d).

Between 120 Ma and 105 Ma, while Mellish Bank was being formed by the Wilkes hot spot, the Kula-Pacific ridge crest migrated over the Lynn hot spot, which produced the east-west trending northern portion of Shatsky Rise and northern Hess Rise. The Farallon counterpart of this east-west ridge is a short north-northeast striking aseismic ridge (Figure 3d).

At 100 Ma the Pacific plate sharply changed direction with respect to the hot spots, resulting in a rapid eastward migration of the Pacific-Farallon spreading ridge with respect to the hot spots [Henderson and Gordon, 1981]. Because the Lynn and Wilkes hot spots were located exclusively under the Pacific plate after 100 Ma, the Farallon aseismic ridges had no Late Cretaceous continuations. The 154- to 100-m.y.-old Farallon aseismic ridges began to be subducted near Cape Mendocino just before 65 Ma. Between 65 and 50 Ma, the point of collision between the north-northeast trending ridge and the north-northwest trending plate margin migrated rapidly southward as the Farallon plate traveled northeast relative to the North American plate. In Figures 3e and 3f the subducted portion of the Farallon aseismic ridge is shown in its predicted location beneath western North America. No correction has been made for the dip of the slab, which has been estimated to have been only 10°-20° [Lipman et al., 1972; Coney and Reynolds, 1977; Keith, 1978].

Uncertainties in Reconstructions

Because our reconstructions critically depend on several assumptions, including the assumption that the hot spots in the Pacific region have been fixed or have moved only slowly relative to those in the Atlantic region, it is difficult to estimate all of the possible errors in our reconstructions. Assuming our correlations between ancient volcanic edifices on the Pacific plate and present-day locations of hot spots are correct, we can, however, make some order-of-magnitude estimates of how accurately the plates are located relative to the hot spots, probably the largest single source of error in the reconstructions. The accuracy of the reconstructions of North America relative to the hot spots has been estimated (W. J. Morgan, personal communication, 1982) to be 500 km. We think the errors of reconstructing the Pacific plate relative to the hot spots are also about 500 km. Therefore the accuracy of the relative location of the Farallon plate and the North American plate is of the order of 10^3 km. Thus we attach no significance to the precise location of the collision along the west coast of the Unites States, but we do think it unlikely, within the context of the assumptions we have made, that the proposed collision began north or south of the western United States.

The convergence velocity between North America and the Farallon plate, 75 to 40 Ma, was 150 km/m.y. [Coney, 1978; Engebretson, 1982]. Because an error of 10^3 km in location translates into an error in timing of the order of 10 m.y., the good agreement between timing predicted by our model and timing of the increased arc-trench distance and magmatic gap seems unlikely to be fortuitous.

The possible errors introduced by our assumptions and interpretations of the seafloor record are difficult to estimate. For example, the details, but not the general features, of our model depend on our interpretation that the major portions of Shatsky Rise and Hess Rise are parts of a continuous feature that was produced by the Wilkes hot spot and that this hot spot lay at or near the ancient Pacific-Farallon spreading center. Nonetheless, the good agreement between the location and timing of collision of the postulated Farallon aseismic ridge and the location and timing of the inferred shallow subduction suggest that this key assumption may very well be correct.

Although our modeled subduction of the aseismic ridge predicts the southward migration of the magmatic lull very well for 65-45 Ma, it does not predict the modest increase in distance of the arc from the trench prior to 70 Ma (Figure 1b). There are several possible explanations. For example, the whole arc may have shifted slightly eastward and the slab shallowed slightly in response to an increase in Farallon-North America convergence velocity at 75 Ma [Engebretson, 1982]. Alternatively, although we limited our model to 154 Ma to present because we know of no hot spot-produced Pacific plate volcanic edifices older than 154 Ma, the Wilkes hot spot may have been active and located beneath the Farallon plate before 154 Ma. Thus there may have been a northeast extension of the aseismic ridge older than we have modeled, which would have collided several million years earlier than in the model we present here.

DISCUSSION

Alternative Models for Shallow Subduction

Four causes for low-angle subduction have been proposed by various investigators: (1) increased net convergence velocity [Luyendyk, 1970; Tovish and Shubert, 1978; Cross and Pilger, 1982], (2) trenchward absolute motion of the overriding plate [Hyndman, 1972; Moberly, 1972; Cross and Pilger, 1978, 1982], (3) decreasing age of the subducting oceanic plate [DeLong and Fox, 1977; Pilger and Henyey, 1979; Cross and Pilger, 1982], and (4) the presence of an oceanic plateau or aseismic ridge on the subducting plate [Kelleher and McCann, 1977; Pilger, 1981; Livaccari et al., 1981; Cross and Pilger, 1982]. Motion of both the North American and Pacific plates with respect to the hot spots show that the net convergence velocity of the North American and Farallon plates was much more rapid 75-40 Ma than before 75 Ma or since 40 Ma [Coney, 1978; Engebretson, 1982]. Similarly, the trenchward absolute velocity of the North American plate was modestly faster 75-40 Ma than before 75 Ma or since 40 Ma [Coney, 1978; Engebretson, 1982]. The increase in net convergence velocity has been the most commonly cited cause for the shallow slab 70-40 Ma [e.g., Coney and Reynolds, 1977; Coney, 1978; Keith, 1978, 1982]. However, because both the net convergence velocity and the trenchward absolute velocity of the North American plate were higher 75-40 Ma not only along the west coast of the United States but along the entire plate margin from Canada to Mexico, neither model correctly predicts the restricted latitudinal distribution over which shallow subduction has been inferred. Similarly, although the age of the subducting slab apparently was continuously decreasing 70-40 Ma as the Pacific-Farallon ridge approached the trench, and although there were several large offsets along fracture zones, such as the Mendocino fracture zone where adjacent parts of the subducting slab differed in age by 40 m.y. [Atwater, 1970], neither effect correctly predicts the restricted latitudinal distribution nor the southward migration with time of the subduction-related volcanism 70-40 Ma [Glazner and Supplee, 1982].

Laramide Deformation

Several lines of evidence suggest that our model can be extended beyond the explanation of the space-time pattern of magmatism 70-40 Ma to the distribution of deformation of the Laramide orogeny. As was the case with the increased arc-trench distance and magmatic gap, Laramide deformation occurred nowhere outside the probable latitudes of the subduction beneath western North America of the Farallon aseismic ridge, and the timing of Laramide deformation, 70-40 Ma, coincides with this subduction event. Moreover, Laramide deformation was more intense in the north than the south [Berg, 1962; Hamilton, 1981]. Our reconstructions suggest that two separate aseismic ridges subducted beneath the United States in the north whereas only one ridge subducted south of 40°N (Figure 3f), thus the observation that Laramide deformation was more intense in the north than in the south might be evidence in support of our model.

If an essential element for Laramide deformation was the subduction of an aseismic ridge on the Farallon plate, and if collision began in the north and migrated to the south as we have suggested, then a reasonable inference might be that the inception of inland deformation should have begun in the north and migrated to the south. Because it is impossible to date deformation as precisely as magmatism, evidence for or against this idea is inconclusive. Nevertheless, Dickinson and Snyder [1978] have suggested that there are hints that deformation did migrate southward with time. In complete analogy with the arguments regarding alternative explanations for the shallowing of subduction during the Laramide orogeny, the main alternatives, that the Laramide deformation was caused by a high Farallon-North America convergence velocity or rapid trenchward motion of North America, fail to explain the latitudinal limits of the deformation within North America.

Because there is such a good fit of our model to three previously unexplained features of the Laramide orogeny, (1) the latitudinal range of the subduction of the Farallon aseismic ridge beneath North America to the latitudinal restriction of Laramide deformation, (2) the southward migration of the buoyant subducted aseismic ridge to the southward migration of the magmatic lull and increased arc-trench distance, and (3) the general timing of the subduction event (70-40 Ma) to the timing of the Laramide orogeny, we feel that subduction of an aseismic ridge deserves serious consideration as one of the principal causes of the Laramide orogeny. We suspect it may have been a combination of several driving forces--rapid convergence rates, rapid trenchward absolute motion, subduction of relatively young lithosphere, and the subduction of a Farallon aseismic ridge--acting together, that caused the Laramide orogeny.

Accretion Versus Subduction

Evidence for the past collision of large aseismic ridges with western North America may be available if portions of the ridges were accreted to the overriding plate. Although the bulk of the proposed Farallon aseismic ridge responsible for shallow subduction 70-40 Ma has been subducted, small portions may have been scraped off and incorporated into the Franciscan Formation. The mid-Cretaceous age of limestones from the Franciscan [Wachs and Hein, 1974, 1975], their Late Cretaceous-early Tertiary age of accretion [e.g., Bailey et al., 1964; Maxwell, 1974; McLaughlin and Pessagno, 1978], and the paleomagnetically determined equatorial paleolatitude of the Franciscan limestones [Alvarez et al., 1980] are all consistent with this hypothesis. The possible accretion of a portion of the Farallon aseismic ridges implies that collision was an important element in the subduction of the ridges between 70 and 40 Ma. However, we think it was not the collision itself, but the shallowing of the dip of the subducting slab due to the presence of the aseismic ridge, that caused the major deformation of the Laramide orogeny [Lowell, 1974; Dickinson and Snyder, 1978].

CONCLUSIONS

The shallow subduction of the Farallon plate beneath North America inferred to have occurred during the Laramide orogeny may have been caused by the subduction of an aseismic ridge on the Farallon plate. The reasoning behind this conclusion is as follows:

1. Magmatic lulls occur today in portions of magmatic arcs where aseismic ridges or seamount chains are being subducted [Kelleher and McCann, 1977; Pilger, 1981; Nur and Ben-Avraham, 1981].
2. Where hot spots are located at or near ridge crests today, aseismic ridges are being formed on both sides of the spreading ridge.
3. Because the Shatsky Rise and parts of the Hess Rise are the same age as their underlying seafloor and therefore were formed at the Pacific-Farallon ridge crest [Hilde et al., 1976; Watts et al., 1980], they were likely to have had counterparts on the Farallon plate.
4. Because most Farallon plate lithosphere has been subducted, any aseismic ridge that rode on it would also have been subducted. By analogy with present-day subducting aseismic ridges, the subduction of a Farallon aseismic ridge may have created a lull in magmatism on the overriding plate.
5. The reconstructed timing and location of the subduction of the modeled Farallon counterparts of the Shatsky Rise and Hess Rise correspond well with the timing and location of the magmatic lull and, specifically, with the time-transgressive southward migration of the magmatic lull of the United States Cordillera 70-40 Ma. Therefore subduction of aseismic ridges was probably a major factor in causing the lull and, by inference, was probably a major factor in causing the Laramide orogeny.

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