
**ROTATION OF CENTRAL AND SOUTHERN ALASKA IN THE EARLY TERTIARY: OROCLINAL BENDING BY MEGAKINKING?**

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**ABSTRACT.** Systematic counterclockwise rotations of paleomagnetic declinations relative to those expected from North American cratonic reference poles are exhibited by latest Cretaceous and early Tertiary volcanic rocks from the western two-thirds of central and southern Alaska. These data suggest that the entire region underwent a tectonic rotation of $44 \pm 11^\circ$ counterclockwise. The most probable rotation mechanism is one that resembles kink folding about a vertical axis, but on a gigantic scale, with the axial plane vertical and nearly coincident with the 148th meridian. The flexural slip required by such megakinking agrees with geological estimates of displacements on known faults. Moreover, this mechanism has the virtue of straightening the sharply bent part of the structural grain of Alaska without opening a huge sphenochasm. A plausible cause of the rotation is convergence between Eurasia and North America, which is predicted to have occurred at the correct time by several analyses of the marine magnetic anomalies in the North Atlantic and Arctic Oceans.

1. **Introduction**

The idea that a large part of Alaska may have undergone significant tectonic rotation goes back at least as far as S. W. Carey's orocline hypothesis (1955). Carey examined the geotectonic consequences of straightening various curved fold belts around the world, including those of Alaska. He concluded that the western two-thirds of Alaska had rotated $28^\circ$ counterclockwise (CCW) with respect to the eastern part since the Triassic, about a pivot point in the Alaska Range near the conspicuous bend in the Denali fault (Fig. 1). Associated with this rotation, Carey believed, was the opening of the Arctic Basin "sphenochasm," which in turn he concluded was driven by a post-Triassic expansion of the earth's radius by twenty percent (Carey, 1958). Although his mechanism involving such a large and recent expansion of the earth appears highly unlikely from our present perspective, Carey's geometrical and tectonic insights have inspired many paleomagnetic investigations around the globe to test for the presence or absence of predicted azimuthal rotations.
Such a test for the Alaska orocline was first attempted by Packer and Stone (1972). They came to a tentative negative conclusion on the basis of a paleomagnetic pole that they obtained from Jurassic sedimentary rocks on the Alaska Peninsula, which suggested clockwise (CW) rotation when compared to the Jurassic North American reference pole. This early work, however, was carried out before the extent of pervasive regional overprinting was generally recognized, when more rudimentary magnetic cleaning was considered sufficient to isolate the primary component. Only blanket rather than progressive alternating field demagnetization was used, and neither thermal demagnetization nor analysis of magnetic components was undertaken. In light of CCW rotations reported just to the north in more recent and detailed studies of latest Cretaceous and early Tertiary rocks, Packer and Stone's early conclusion needs to be reconsidered. In this paper we summarize those results, analyze their implications, and discuss mechanisms that could have produced CCW rotation.

Two subsequent models for the formation of the orocline were proposed somewhat after Carey's. In one, northern Alaska rotated 70° CCW away from the Canadian Arctic Islands about a more northerly pivot point sometime between the Late Jurassic and Late Cretaceous, opening the Canada Basin in its wake and producing intense folding and thrusting in the Brooks Range (Tailleur, 1969 and 1973; Rickwood, 1970). The paleomagnetic data bearing on this model are discussed in a companion paper in this volume by D. B. Stone. In the other model, which figures prominently in the present paper, the western two-thirds of central and southern Alaska rotated 40 to 55° CCW during latest Cretaceous and Early Tertiary time (Grantz, 1966). In contrast to the earlier ideas of Carey (1955), rotation is accommodated not simply by the pivoting of one large block, but by sympathetic movement of several narrower blocks separated by major strike-slip faults, much like one limb of a huge kink fold with its vertical axial plane coinciding approximately with the 148th meridian (Fig. 1). Note that neither of these subsequent models excludes the other, because the rotations that are invoked by each occur at different times and involve different parts of Alaska.

2. Paleomagnetic Evidence

The region of direct concern for this paper lies south of the Kaltag fault and west of the 148th meridian, an area of more than 400,000 square kilometers in central and southern Alaska (Fig. 1). The paleomagnetic data available are almost entirely derived from lava flows of Latest Cretaceous and Tertiary age. Lava flows are very reliable recorders of the paleomagnetic field, and their primary high-temperature thermoremanent magnetization is often easier to distinguish and separate from secondary overprints than is the case for the remanent magnetization of sedimentary rocks. However, it is usually more difficult to determine the structural correction necessary to restore lava flows to their pre-folding orientation and to sample a sufficient span of time well enough to average out secular variation of the paleomagnetic field. This is important because even relatively small errors in paleomagnetic direction translate into significantly large errors in paleomagnetically inferred tectonic rotation at high latitudes, where the inclination of the field is steep. A more detailed discussion of the relative merits of lava flows and sediments for tectonic studies and of strategies to minimize the above difficulties can be found in Coe et al. (1985) and Thrupp and Coe (1986).

The locations of all but one of the paleomagnetic studies and the tectonic rotations inferred from them are shown in Figure 1. The reference poles required to calculate these rotations relative to North America were interpolated from the lists of Irving and Irving (1982) and Diehl et al. (1983) and are given in Coe et al. (1985). In all studies stepwise thermal and alternating-field
demagnetization were performed, and the stable components that were isolated by the two methods yielded mean directions that are comparable and, with one exception, have 95 percent confidence limits between 4 and 8°.

Figure 1. Simplified tectonic map of Alaska (after Patton and Tailleur, 1977) showing conspicuous bends in great faults that mark the "oroclone" in central and southern Alaska, evidence for east-west compression in northwest Alaska, and sites of Late Cretaceous and early Tertiary paleomagnetic studies. Paleomagnetically inferred tectonic rotation relative to North America is indicated at each site, with 95 percent confidence limit of the rotation depicted by the half-angle of each stippled fan: (1) Bristol Bay flows, 39±23° CCW; (2) Lake Clark lava flows, 55±28° CCW; (3) Yukon River tuffaceous sediments, 77±37° CCW; (4) Blackburn Hills lava flows, 38±23° CCW; (5) Teklanika lava flows, 29±99° CCW; (6) Talkeetna lava flows, 37±48° CCW.
Progressing generally from west to east and south to north in Figure 1, we now describe briefly each of the paleomagnetic studies.

2.1. BRISTOL BAY REGION, SOUTHWESTERN ALASKA.

A CCW rotation of 39±23° was found in a study of 84 latest Cretaceous lava flows from the Bristol Bay region in southwestern Alaska (Globerman and Coe, 1983a; Globerman, 1985). Three of these flows have been radiometrically dated by the K-Ar method, giving a mean age of 68±3 Ma. Two well-exposed sections comprising about 1800 and 2700 meters of stratigraphic thickness were sampled on three islands along the northern coast of Bristol Bay. The flows are mostly subaerial, and selected trace-element ratios and Rare Earth Element patterns are consistent with eruption in an island arc setting. Bedding attitudes were determined unusually well from both sedimentary interbeds and clearly defined flow boundaries. Each section dips homoclinally, but the variation in attitudes between them is 70°. The regional tilt test (McFadden and Jones, 1981) indicates a pre-folding age of magnetization at greater than 99 percent confidence, supporting our belief that the characteristic component is primary. However, all of the flows have normal polarity, raising the question of whether they might have been erupted in a time too short to average out secular variation adequately. Other evidence suggests that this is not so. From latest Cretaceous to early Paleocene time there are several periods of normal polarity lasting as long as 0.5 to 1.0 Ma within which the entire sequence could have been erupted. The large number of flows, thickness of section, and numerous sedimentary interbeds suggests to us that the sequence spanned at least several tens of thousands of years. Moreover, the angular dispersion is consistent with a full sampling of secular variation, as is the presence of three geomagnetic excursions recorded in the sequence. The 10 deviant flow mean directions that record these excursions were excluded from the final formation mean.

2.2. LAKE CLARK REGION, SOUTHWESTERN ALASKA.

A CCW rotation of 55±28° was found 350 km to the northeast of (1) by Thrupp and Coe (1986) in a study of 30 Paleocene (?) basaltic lava flows just north of Lake Clark. Several scattered K-Ar dates for these flows indicate an Eocene or Paleocene age. Ten better K-Ar determinations on more acidic plutons and extrusive rocks in the same general area are consistent with a Paleocene age. The range of possible ages does not significantly affect the inferred CCW rotation because the reference pole did not move very much during that interval. The flows are contained in two shallowly dipping sections about 4 km apart, and collectively comprise a sequence of at least 200 m that spans several reversal boundaries and includes many soil and ash layers. Thus it is likely that the samples average at least several hundred thousand years of secular variation. Reasonably reliable mean bedding attitudes were constructed for each section from apparent dips shot from a distance, but they were too similar to allow a conclusive fold test. Closely antipodal normal and reversed directions, however, afford a positive reversal test, adding support to our contention that the remanence is primary and that secular variation has been sufficiently averaged to obtain a good approximation of the axial dipole field.
2.3. LOWER YUKON RIVER, WESTERN ALASKA.

A much less well constrained CCW rotation of 77±37° was found 400 km to the northwest of (2) by Gliberman et al. (1983b) in a study of Lower Cretaceous tuffaceous sediment exposed along the Yukon River. Twenty-seven sites spanning 1500 meters of stratigraphic thickness all yielded normal polarity. At three of them an individual sample revealed a reversed characteristic direction after removal of a large normal overprint. A weak fold test was inconclusive, but did demonstrate a small increase in scatter after tectonic correction. For all these reasons the characteristic remanence is probably a secondary normal overprint, but its direction is entirely distinct from that of the recent field. Assuming that it was acquired at 70 Ma, the time of peak magmatic activity in the region, and that no tilting occurred after that time, the paleomagnetically inferred rotation is 77° CCW. Exploring the consequences of other plausible assumptions, such as increasing the age of the overprint by 20 to 50 Ma or allowing up to 30 percent of the folding to be post-remagnetization, the amount of rotation can be cut in half but always remains significantly CCW.

2.4. BLACKBURN HILLS, WESTERN ALASKA

A CCW rotation of 38±23° was found 200 km to the north of (3) by Thrupp and Coe (manuscript in preparation) in a study of 42 Paleocene basaltic-andesite flows from the Blackburn Hills, a little south of the Kaltag fault and west of the Yukon River. Published K-Ar ages from this igneous complex range from 56-65 Ma (Moll and Patton, 1982), and later unpublished determinations also point to an age of about 60 Ma. Three sections, each 200 to 400 m thick, were sampled on both limbs of a large syncline. We took local bedding attitudes wherever possible in the field, but the attitudes that we employed for the structural corrections were obtained by least-square fitting planes to points obtained by a technician of the Topographic Maps Division of the U. S. Geological Survey, who used a PG-2 stereo plotter on traces of individual lava flows that are visible on the aerial photos. The fold test resulting from these highly precise and unbiased structural corrections is positive at a very high confidence level. In addition, a positive reversal test is also obtained, strongly suggesting that the characteristic remanence is primary and that secular variation has been adequately averaged. Qualitative support for this CCW rotation is provided by a rotation of 60±40° reported by Harris et al. (1987) for several lava and pyroclastic flows that are exposed nearby along the Yukon River and dated at about 55 Ma.

2.5. CANTWELL BASIN, CENTRAL ALASKA.

A CCW rotation of 29±99° can be estimated from the results of the study by Hillhouse and Grommé (1982) on 18 flows of the Teklanika Volcanics associated with the Paleocene Cantwell Formation, located 550 km to the east of (4) between the two major strands of the Denali fault. The 95 percent confidence limit on the rotation is very large because the alpha-95 circle around the paleomagnetic pole contains the sampling site as well. K-Ar dates indicate an age of 60 Ma or perhaps slightly older. The generalized fold test is strongly positive. No reversal test is possible because all the flows have reversed polarity. The main argument that sufficient time had probably been sampled to average out the effects of secular variation was that the flows were sampled over a large geographical area. Additional sampling of 16 Teklanika lavas has been carried out by Panuska and Macicak (1986). Depending on the method they use for combining and averaging flows in the two
data sets, CCW rotations ranging from 12 to 32° are obtained (B. Panuska, personal communication, 1987).

2.6. TALKEETNA MOUNTAIN REGION, SOUTHERN ALASKA.

A CCW rotation of 37±48° can be calculated from the results of Hillhouse et al.'s (1984) study of 26 Eocene lava flows in the Talkeetna Mountains, 75 km to the south of (5). K-Ar ages from these and associated intrusive rocks give an age of about 52 Ma. The sampling localities were spread over a large area, and both fold and reversal tests were positive. Additional sampling of 24 of these Eocene flows further to the south by Panuska and Stone (1985) yielded a mean direction only 3° different from that of the former study. A detailed account of this latter study is nearing publication (D. B. Stone, personal communication, 1988), and it is possible that combination of the two sets of data will reduce the error to the point that the rotation is significant at 95 percent confidence.

2.7. McGRATH REGION, WEST-CENTRAL ALASKA.

A CW rotation of 2° was obtained by Plumley (1984) in a study of seven lava flows of the Paleocene Nowitna Volcanics, 350 km to the northwest of (6) in the McGrath region (not shown on Fig. 1). The small number of flows leads to a much larger uncertainty in the mean direction than for the other studies, and thus, for the same reason as in (5) above, a huge and poorly defined uncertainty in the paleomagnetically inferred rotation. Moreover, exposures were poor, so that attitudes had to be estimated from sloping benches that formed on the hillsides above some of the flows. Even though the flows have only moderate dip, the structural correction is probably also the most uncertain of those used in this paper. After removal of large, scattered overprints due to lightning, reversed directions were found for six of the flows and a stable, intermediate direction for the seventh (excluded from the final mean). Although no fold or reversal test is available, we have no reason not to suppose that the characteristic remanence is primary. Moreover, the lack of serial correlation in the directions and the presence of an intermediate (excursion?) direction suggest that the flows span at least a couple of thousand years. Although that is shorter than one would like for averaging out the effects of secular variation, the time-average of the geomagnetic pole during the past 2,000 years does approximate the geographic axis fairly well (Champion, 1980). Thus we are reluctant to exclude this result, but its extremely large uncertainty must be kept in mind.

3. Discussion

3.1. THE CASE FOR REGIONAL ROTATION

The azimuthal rotations inferred from the above paleomagnetic studies show a strong CCW bias. Although the validity of even the best determined of these rotations taken alone might be doubted, owing to the sensitivity of the paleomagnetic declination to systematic errors because the inclination is steep, the consistency of the sense of rotation from study to study is difficult to dismiss. Only one of the seven studies (7) gives a small CW rotation, and it is by far the most uncertain of all the results. Weighting all seven equally without regard to confidence limits gives a mean CCW rotation of 39±19, where the plus or minus value is the 95 percent confidence interval of the mean.
Restricting the average to the three results (2.1, 2.2 and 2.4) that are each clearly significant at the 95 percent confidence level, the mean rotation is $44\pm11^\circ$ CCW.

It is important to note in passing that little or no latitudinal movement relative to North America is implied by the paleomagnetic results. The values of northward displacement derived from the seven studies range between $-8$ and $+9^\circ$ and have a mean value of $2\pm4^\circ$. Only one of them is significant at 95 percent confidence. Recalling that $9^\circ$ of northward displacement at these high latitudes corresponds to only $5^\circ$ shallowing of inclination, it appears unwarranted to make any tectonic interpretation based on the geographic distribution of the apparent northward and southward displacements.

3.2. ROTATION MECHANISMS

The pronounced CCW bias of the azimuthal rotations strongly suggests the operation of some kind of regional rotation mechanism. A number of possibilities come to mind:

3.2.1 Simple Oroclinal Bending. Carey's (1955) classic orocline hypothesis, adapted to explain the post-latest Cretaceous rotations presented in this paper, implies either great extension or great shortening of the crust, neither of which fits the geological record. The rotational pivot point favored by Carey himself would require the opening of a huge sphenochasm in Alaska that is simply not observed (Fig. 2). A pivot point much farther north in the Mackenzie River delta has the virtue of explaining the opening of the Canada Basin, but then requires great east-west compression.

Figure 2. Simple orocline bending model of Alaska. Regional CCW rotation of the amount implied by the paleomagnetic results would open a huge sphenochasm.
to the south that is also not observed. Moreover, the Canada Basin opened before the rotation of central and southern Alaska that is of concern here (Sweeney, 1985).

3.2.2. Local Rotations In Transcurrent Shear Zones. In two seminal papers, Beck (1976 and 1980) demonstrated that the systematic CW declination anomalies found in numerous paleomagnetic studies of rocks along the western margin of North America occurred as block rotations in the right-lateral megashear zone associated with the transform and oblique subduction boundaries that existed from late Mesozoic to the present time between the North America and the Pacific, Farallon, and Kula plates. This would appear at first glance to be a promising explanation for systematic rotations in Alaska. The tectonic map of Alaska is dominated by a series of long, parallel strike-slip faults that pass through the region of interest, and several of the study sites are close to one or the other of them (Fig. 1). The geologically inferred sense of offset on all of these faults, however, is right-lateral (Grantz, 1966; Patton, 1973; Lanphere, 1978), the opposite of what is needed to explain the observed CCW rotations by Beck's hypothesis.

Even earlier, Freund (1970 and 1974) examined the kinematics of block rotations in transcurrent shear zones accommodated by strike-slip displacement on bounding cross-faults. Many of his ideas are supported by results of later studies combining paleomagnetic and structural information (Luyendyk et al., 1980; Ron et al., 1984; Wells and Coe, 1985; Homafius, 1985; Wells and Heller, 1988), and they have been given a firm mechanical basis by Nur et al. (1986). One geometrical case considered by Freund (1974) predicts CCW rotation in a right-lateral shear zone, and thus is potentially capable of explaining the 44±11° CCW paleomagnetic rotation of southern and central Alaska. To do so, however, would require that the entire region was subdivided into elongate blocks by numerous east-west cross-faults between the southwesterly trending master faults (Fig. 1), evidence for which is presently lacking. Moreover, the observed rotation of 44° lies at the upper limit of what can be expected mechanically with only one such set of cross-faults (Nur et al., 1986).

3.2.3. Rotations of Blocks Pushed Around Sharply Bent Faults. Stout and Chase (1980) pointed out that some or all of the curvature of structural grain in Alaska that has been termed the Alaska orocline might in fact be original. A crucial feature for their model is that the sharply curved part of the Denali fault can be closely approximated by a small circle. They applied this idea to that segment of the fault by assuming locally rigid plates, and were able to explain with considerable success the orientation and sense of displacement of secondary faults in the area. Their model also provides a plausible mechanism for significant azimuthal rotation of terranes south of and close to the big bend in the Denali fault.

Recently this model has been adapted on a much larger scale by Panuska (1987) to the Tintina-Kaltag fault system (Fig. 1) in an attempt to account for paleomagnetically rotated blocks far beyond the sharp bend. There are at least two major difficulties to this explanation. First, fault displacements much larger than geologically inferred offsets would be required for the terranes of westernmost Alaska to have passed around the bend. For instance, to account for the paleomagnetically inferred rotation of the Blackburn Hills by this model, a displacement of at least 750 km on the Kaltag fault since the Early Paleocene would be needed, more than three and a half times the well documented offset since Late Cretaceous time (Grantz, 1966; Patton, 1973). Moreover, Kula plate motion relative to North America throughout the early Tertiary was not in a direction that could have pushed a block along the Kaltag or Farewell faults in their present orientations (Engebretson, et al., 1985). Second, both the Denali-Farewell and the Tintina-Kaltag fault systems depart markedly from small-circle geometry on this scale (Fig.3), so that pushing terranes into, around, and out of the sharp bends in either of these fault systems would be
mechanically difficult. It would necessitate significant compression followed by compensatory extension to satisfy the spatial constraints imposed by the radically varying curvature of the backstop, and would leave a complex structural imprint that is not apparent in the rotated rocks of western Alaska.

Figure 3. "Railroad car" model—rotation produced by pushing blocks around curved faults, as suggested by curved arrows. Small circles drawn about solid dot illustrate that, on the large scale, the fit of the Denali-Farewell and Tintina-Kaltag fault systems to small circles is not very good. Straight arrow shows average direction of motion of Kula plate in Alaska region (fixed North America reference frame) for the interval 74 to 43 Ma, not a favorable orientation for pushing blocks in the direction supposed by this model. Moreover, the geologically inferred offsets on the Kaltag and Farewell faults are much too small to produce the observed paleomagnetic rotations (Figure 1).

The poleward displacement of the most outboard terranes of Alaska and their collision with the Alaska backstop during late Cretaceous and early Tertiary time that is documented by paleomagnetic (e. g., Coe et al., 1985) and geological (e. g., Csejtey et al., 1982) evidence prompts an analogy to the indentation and extrusion tectonics used to describe the India-Asia collision (e. g., Molnar and Tapponnier, 1975; Tapponnier et al., 1983). The significantly greater curvature of the tectonic grain in southern Alaska compared to that farther north (Fig. 1) does suggest intensification by indentation from the south, and recent structural data around the Gulf of Alaska support this idea (Bol et al., 1987). For the same reasons given in the paragraph above, however, extrusion around a
The sharply curved backstop is not a likely explanation for the paleomagnetic rotations observed many hundreds of kilometers to the west.

3.2.4. Megakinking. The explanation that best fits the available paleomagnetic, geological, and plate tectonic evidence is the "megakink" version of the oroclinal hypothesis, first suggested by Grantz in 1966. As mentioned in the Introduction and illustrated in Figure 4, this model supposes that bending of Alaska occurred in response to northwest-southeast compression by a mechanism analogous to kink folding about a vertical axis. The zones of weakness that accommodated the right-lateral flexural slip required by such folding were the pre-existing Kaltag, Iditarod, Farewell, and Castle Mountain-Lake Clark faults that now divide central and southern Alaska conspicuously into northeast-southwest trending strips (Fig. 1). The axial plane of the kink runs more or less along the 148th meridian, and the eastern limb is postulated not to have rotated, a reasonable constraint because it is backed up by all of North America.

Applying the geometrical relationships for such folding, Grantz (1966) showed that the best estimates for displacement on these faults since Late Cretaceous time predict CCW azimuthal rotations of 30 to 55° of central and southern Alaska. This range is in excellent agreement with the paleomagnetically inferred rotations, and is also the right order to straighten the structural grain of Alaska in the sharply bent region. Moreover, in contrast with the prediction of simple oroclinal bending, the megakink mechanism does not require the opening of a giant sphenochasm (c. f. Fig.

Figure 4. Megakink model of rotation of Alaska. Simultaneous rotation of fault-bounded blocks by the paleomagnetically inferred amount, possibly in response to Eurasia-North America convergence, produces the correct sense and approximately correct displacement on faults, and also does not open a giant sphenochasm.
2 and 4). Finally, another attraction is that the existence of a more gently curved ancient continental margin than at present would have facilitated the large northward displacements of southern Alaskan terranes during Cretaceous time that are indicated by other paleomagnetic results (Hillhouse, 1977; Coe et al., 1985; Thrupp and Coe, 1986).

The key element of Grantz's (1966) model is block rotation accommodated by strike-slip displacement on bounding faults, and thus is similar to the later, more detailed kinematic models of Freund (1974) and Garfinkle (1974). The enormous scale of the rotated blocks, however, is unprecedented. We use the term "kink" in this paper because Grantz originally stressed the idea of flexural slip folding about a vertical axis, and "kink" conveys the idea that distributed deformation is localized around the hinge region. As is evident from Figure 1, the hinge boundary of the Alaska "megakink" is not mathematically sharp. Figure 4 neglects the complex deformation around the hinge as well as problems of extension or compression normal to the strike-slip faults, and should be regarded as an illustrative cartoon rather than an accurate kinematic representation. Moreover, it does not show how rotation of such a large part of Alaska could be accommodated at its other boundaries. We will return to this latter topic shortly.

In summary, we should emphasize that the paleomagnetic data themselves do not prove the rigid or even quasi-rigid behavior of the regions between the major strike-slip faults in central and southern Alaska. The density of determinations is low and the uncertainties in declination, and thus in paleomagnetic rotation, are necessarily large because of the steep inclination of the field. Moreover, even perfect paleomagnetic data cannot delineate the block size in a region undergoing uniform rotation. What can be concluded is that, considering both the paleomagnetic and dating errors, the data allow the hypothesis of uniform rotation of this part of Alaska by 35 to 55° CCW. In combination with the regional geological evidence, the case for block rotation on this large scale becomes more convincing. The first order discontinuities apparent in the field and on aerial photos are indeed long, straight faults, and the geologically inferred strike-slip offsets across them are consistent in both sense and magnitude with those required to produce the mean paleomagnetic rotation by rigid rotation of the intervening blocks. To test further the integrity of these blocks and the degree of accommodation of the regional CCW rotation by right-lateral displacement on these prominent faults, however, will require extensive field and structural studies to refine estimates of timing and amount of offset, to search for less obvious sets of faults that might have played an important role, and to evaluate the contribution of smaller scale, more continuous deformation in both the limb and the hinge zone of the presumed "megakink."

3.3. CAUSE OF ROTATION

Thirty years ago Carey (1958) had already linked his idea of the Alaskan orocline with the opening of the Arctic Ocean, and, indeed, of the entire Atlantic Ocean as well. He drew attention to the similarity between the rotation angle of 28° that he estimated for the Arctic Ocean sphenochasm and the 30° angle between the Cretaceous-Tertiary portions of the North American and European apparent polar wander paths (Irving, 1958). However, opening of the relevant part of the Arctic Ocean (the Canada Basin) is now dated at 140 to 80 Ma (Sweeney, 1985), too early to drive the rotation of central and southern Alaska that we are concerned with here. Moreover, Carey's geometrical argument for linking opening with bending was based on different, more gently curved structural trends that run westward through northern Alaska.
Grantz (1966) called upon Eurasia-North America convergence to produce the Late Cretaceous-Early Tertiary rotation of central and southern Alaska. He also referred to paleomagnetic evidence for the opening of the Atlantic Ocean during that time, but emphasized the concomitant eastward movement of Siberia toward North America that such opening implied. Patton and Tailleur (1977) extended the picture to the north, suggesting that northwestern Alaska and eastern Siberia buckled and shortened under the east-west compression (Fig. 1). They further supposed that this compressive deformation was largely decoupled by the Kaltag fault from the block rotation that was occurring simultaneously to the south.

Comparison of the recent paleomagnetic data defining the rotation with plate-motion models provides a further test of Grantz's model. The paleomagnetic evidence cited above demonstrates a CCW rotation of $44 \pm 11^\circ$ since about 65 Ma. Thirty million years or less later most of the rotation was complete, as indicated by other paleomagnetic results of Thrupp (1986), derived from more than 70 flows from 12 localities widely distributed on the Alaska Peninsula with average age 35 Ma, that yield a small and statistically insignificant CCW rotation of $11 \pm 26^\circ$. Pitman and Talwani (1972), in the first detailed plate-motion analysis of the opening of the North Atlantic using marine magnetic anomalies, noted that their results implied Eurasia-North America convergence during Late Cretaceous and early Tertiary time. Later analyses have upheld their conclusion. Thus the timing of convergence fits the paleomagnetic observations well.

In principle, the plate-motion analyses also allow a quantitative test of the model. Using the more detailed analysis of Srivastava (1978), which is similar to that of Pitman and Talwani, Coe et al. (1985) calculated that the amount of convergence between Siberia and Alaska was sufficient to have caused a maximum of $43^\circ$ of CCW rotation of southern and central Alaska between 67 and 53 Ma. This startlingly close agreement between the land-based paleomagnetic and the marine magnetic observations, however, appears to have been merely a coincidence in light of more recent analyses of the sea-floor anomalies, including one by Srivastava and Tapscott (1986) in which the convergent displacement during the time of interest is reduced to one-third of the previous value. As noted by Harbert et al. (1987), the main problem is that the stage poles defining the ocean opening lie too close to the Arctic region, so that the uncertainty in their positions radically affects the magnitude and direction of the relative motions. Nonetheless, from a qualitative standpoint the plate-motion models are in reasonable agreement with the hypothesis that rotation was driven by Eurasia-North America convergence.

3.4. BOUNDARIES OF THE ROTATED REGION

An important question that arises when we try to fit the rotation scenario into the tectonic history of the rest of Alaska and the Arctic is the location and nature of the boundaries of the CCW rotated region. Where and how was the rotation accommodated spatially? The eastern boundary is the hinge region of the presumed megakink, which, as we have already noted, lies in the vicinity of the 148th meridian. The northwestern boundary is covered in part by the Bering Sea, but is probably a broad and complex zone of distributed deformation recording Siberia-Alaska convergence (Fig. 1). The southern (southwestern and southeastern) boundary was a subduction zone where, during the interval of interest, the Kula plate, and, at the very end, the Pacific plate dived beneath Alaska (Engebretson et al., 1985). In the southwest it was probably at the Bering Sea shelf until, in early Tertiary time, it stepped back and formed the present Aleutian Arc (Scholl et al., 1975). Farther east in southern Alaska its precise location as a function of time is complicated by questions concerning the timing of arrival of exotic terranes. The important point for our purposes, however, is not
exactly where it was, but that it was a subduction boundary, because subduction provides a natural means of accommodating the hundreds of kilometers of southeasterly displacement of western Alaska relative to North America that are required by the megakinking model.

An unresolved and critical problem, however, is the northern extent of the rotated region. As mentioned above, the Kaltag fault is a probable boundary (see Fig. 1 and also Patton and Tailleur, 1977). Also consistent with this limit is the paleomagnetic result of Harris et al. (1987) on overprinted rocks just north of the Kaltag fault. Using their estimated age of 50 Ma for the overprinting and supposing, on the basis of the strongly negative fold test, that little or no post-remagnetization deformation occurred, we calculate only 2±3° of CCW rotation since 50 Ma. If the boundary of the rotated region is the Kaltag fault, however, then substantial extension must have occurred in latest Cretaceous and early Tertiary time to the north of it. In fact, there is a huge triangular basin, the Yukon-Koyukuk basin, south of the Brooks Range and mainly north of the Kaltag fault that, in terms of its size, shape, and position, could account very well for much of the required extension. The problem is that it is filled with Cretaceous sediments that are apparently older than the various volcanic units that record the rotation (Patton, 1973). Could a major part of the extension in this basin have occurred substantially later than is presently believed? If not, where else could the extension be taken up? In normal faulting distributed throughout northwestern Alaska? Offshore even farther to the north? Further paleomagnetic, structural, and seismic data are needed to answer this question, as well as other questions concerning the position and the nature of the lower boundary of the rotating blocks.

4. Conclusions

Systematically CCW azimuthal rotations relative to North America are demonstrated by six of seven paleomagnetic studies of latest Cretaceous and early Tertiary volcanic rocks in the western two-thirds of southern and central Alaska. The CCW bias is highly significant statistically: the mean CCW rotation for all seven results is 39±19°, whereas for the three best results it is 44±11°. These data appear to record a regional rotation of an area greater than 400,000 square kilometers in southern and central Alaska that lies west of the 148th meridian and at least as far north as the Kaltag fault. Additional paleomagnetic results suggest that most or all of the rotation was completed by 35 Ma.

The most probable rotation mechanism is oroclinal bending by megakinking; that is, simultaneous rotation of at least four elongate blocks in a manner analogous to the rotation of one limb of a huge kink fold about a vertical fold axis. Convergence at the appropriate time between Siberia and North America, predicted by most analyses of marine magnetic anomalies in the North Atlantic and Arctic Oceans, provides a plausible motive force. The flexural slip required by the megakinking mechanism to accomplish the paleomagnetically observed rotation agrees with geological observations of offsets, which have both the expected sense and approximately correct amount of displacement, on prominent strike-slip faults bounding the blocks. This mechanism has the advantage of straightening the structural grain of Alaska without opening an enormous sphenochasm where one is known to exist. Moreover, the more gently curved continental margin would conveniently facilitate the northward translation of the most outboard terranes of southern Alaska during Cretaceous and early Tertiary time that is demanded by other paleomagnetic data. Unresolved questions remain, however, concerning the northern extent of the rotated region and the manner in which the extension that is expected to the north of it was accommodated.
Acknowledgments

This research was supported by National Science Foundation Grants EAR-8417369 and EAR-8609784, and by grants and logistical support from the U. S. Geological Survey, Arco Alaska, Arco Oil and Gas, Amoco Production Company, Mobil Exploration and Producing Services, and Exxon Production and Research Company.

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