Paleomagnetic Results from Alaska and Their Tectonic Implications

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We present the results from seven of our paleomagnetic studies in Alaska and collect and evaluate the results of 21 others from the literature. The results from lava flows are generally more consistent and reliable than those from sedimentary rocks. The discrepancies may be explained by depositional induced inclination error and by undetected secondary overprinting in sedimentary rocks. Using the most reliable results and other selected data, we propose the following tectonic scenario for terrane accretion in southern Alaska. Terranes north of the Peninsular terrane were essentially in place by latest Cretaceous time. The paleomagnetic data suggest, however, that much of western and central Alaska has rotated about 40° counterclockwise about a vertical axis since then, in agreement with an earlier model of Grantz (1966) based on geological grounds. A major cause of the rotation was convergence between Eurasia and North America. The Peninsular terrane and Wrangellia collided with North America in the vicinity of present-day Cape Mendocino in mid- to Late Cretaceous time, about 20° south of their present position with respect to cratonic North America. Together with the associated Jura-Cretaceous flysch belt formed during initial convergence with North America, they were moved northwestward along strike-slip faults parallel to the ancient margin by oblique subduction of the Kula plate, arriving at interior Alaska some time before 52 Ma. The Prince William and Chugach terranes lay about 25° to the south of their present positions of 62 Ma ago and were also driven north by oblique subduction of the Kula plate and, after 42 Ma, the Pacific plate. Slivering by inter- and intraterrane dextral transcurrent faulting accommodated the post-52-Ma relative motion required by the paleomagnetic results between the most outboard part of the Prince William terrane and the most inboard part of Wrangellia.

INTRODUCTION

During the past dozen years, investigation and reinterpretation of the geology of Alaska have shown that the state consists of a large number of terranes that are characterized by disparate geological records (Jones et al., 1972, 1981, 1983; Coney, 1980). Natural questions to ask about each of these tectonostratigraphic terranes are where it came from and when it arrived at its present position relative to other terranes. Although tectonostratigraphic terranes by definition are fault bounded and have geological histories distinctly different from those of their neighbors prior to juxtaposition, they may or may not have undergone large relative displacements (Jones et al., 1983). Paleomagnetism is most helpful in answering these questions. With enough reliable paleomagnetic data one can make quantitative estimates of paleolatitude and paleogeographic orientation, and thus one can estimate as well north-south displacement and azimuthal rotation relative to continents or other terranes. In this paper we deal with the paleomagnetic evidence concerning the last stages of assembly of the collage of Alaskan tectono-stratigraphic terranes—that is, with central, south-central, and southwestern Alaska during Late Cretaceous and Early Tertiary time.

Wrangellia (Fig. 1) is the Alaskan terrane that has been shown most clearly to be highly allochthonous. Both paleontological (Jones et al., 1977; Newton, 1983) and paleomagnetic (Hilhouse, 1977) evidence from Wrangellia point to a lower paleolatitude during Late Triassic time, implying that it traveled northward at least several thousand kilometers relative to the North American craton before it was emplaced in its present location. Jurassic and Cretaceous paleomagnetic data obtained even earlier by Stone and co-workers (Packer and Stone, 1972, 1974; Stone and Packer, 1977, 1979) suggest that the Peninsular terrane (Fig. 2) also was far to the south. This is consistent with a recent paleontological interpretation (Newton, 1983) that Wrangellia and the Peninsular terrane were in the same general region in the Late Triassic and with stratigraphic evidence that they were amalgamated by Late Jurassic time (Jones and Silberling, 1979).

Neither the paleomagnetic nor the geological evidence alluded to so far could distinguish between northern and
Figure 1—Latitudinal displacement and azimuthal rotation inferred from paleomagnetic results of our studies listed in Table 1. See legend and caption of Figure 2 for explanation of symbols.

The contradiction has been sharpened by several recent paleomagnetic results from Upper Cretaceous and Lower Tertiary volcanic rocks inboard of Wrangellia and the Peninsular terrane that imply little or no latitudinal displacement relative to North America. One of these studies (Hillhouse and Grommé, 1983a) even laps onto northernmost Wrangellia. However, the paleomagnetic results indicating large poleward displacements for the southern terranes (Wrangellia, Peninsular, Chugach, and Prince William) are so numerous that they demand serious consideration.

In this paper we briefly present our own data that bear on this problem. We then summarize and evaluate the considerable body of paleomagnetic results from Late Cretaceous onward for all but the southeastern part of Alaska. Finally, based on a selection of these data, we give our own interpretation (and speculation) concerning the latitudinal displacement (and speculation) concerning the Alaskan terranes.

PALEOMAGNETIC RESULTS FROM UCSC LAB

During the past 5 years we have put considerable effort into the study of Alaskan terranes, with particular emphasis on the questions and problems raised above. In this section we describe the results of a number of our studies that have important bearing on these problems. Two of these studies are published in recent articles, and the others are in press or in preparation at the time of writing. Readers wishing more details of these studies should consult those references. The purpose here is to gather the main results together and to present them in a coherent framework.

Ghost Rocks Lava Flows, Kodiak Island

On Kodiak Island we conducted a paleomagnetic study of lava flows in the Paleocene Ghost Rocks Formation at two localities that are separated along strike by about 80 km (50 mi) (Plumley et al., 1982, 1983). These andesitic and basaltic flows are interbedded with sandstone and argillite, which make up the bulk of the formation, and the whole mass is intruded locally by distinctive
Figure 2—Latitudinal displacement and azimuthal rotation inferred from paleomagnetic studies listed in Table 2 (no. 4 omitted, see text). Bold accented symbols indicate results derived from studies of lava flows. Base is Alaska terrane map of Jones et al (1984), but incorporating some simplifications found in the circum-Pacific terrane map of Howell et al (1983). See those references for abbreviations of terrane names.
The mean primary directions of the flows at Kiliuua and Alitak Bays after structural restoration to paleohorizontal (see Table 1, stratigraphic coordinates) differ by 122° in declination. This discrepancy suggests that a large tectonic rotation between the two areas has occurred, a frequent occurrence near both convergent and strike-slip boundaries (e.g., Beck, 1976, 1980). Indeed, the strikes of Alitak Bay are rotated in the same sense as the declinations relative to those at Kiliuua Bay, though not enough to explain the entire discrepancy by simple rotation about a vertical axis. The mean inclinations differ by 12°, a much smaller but still significant discrepancy. The most likely explanation is a combination of (1) incorrect structural correction resulting from initial dips and errors in measuring the bedding attitudes, and (2) incomplete averaging of geomagnetic secular variation by the lava flows sampled.

The most important finding of this study is that the mean inclination of the primary remanence is significantly shallower than that which would be expected if the lava flows of the Ghost Rocks Formation had been in their present position relative to cratonic North America when they recorded the geomagnetic field direction about 62 m.y. ago. This result strongly suggests that these rocks were considerably further south with respect to North America in Early Paleocene time. Taking the paleomagnetic result of each area at face value, the discrepancy in paleolatitude is 31 ± 9° for Kiliuua Bay and 16 ± 9° for Alitak Bay. (See Appendix A for method and assumptions used in calculating latitudinal displacements, azimuthal rotations, and their uncertainties.) Since the two areas are composed of very similar rocks of the same formation and are presently separated by only 80 km (50 mi) along strike, it is likely that the differences in inclination found do not stem from actual differences in paleolatitude, but rather from reasons such as those mentioned in the paragraph above. Therefore, the results have been combined, using colatitude statistics (McFadden and Reid, 1982), to obtain an overall estimate for the paleolatitude of the Ghost Rocks Formation of 40 ± 6° N. The expected paleolatitude, calculated from the North American reference paleomagnetic pole for 60 Ma or 65 Ma (Table 4), is 65 ± 3 or 68 ± 5°, respectively. Using the former value, we conclude that the Ghost Rocks Formation has moved northward relative to North America by 25 ± 7°. (Any longitudinal movement is, of course, indeterminate by conventional paleomagnetic methods.) This conclusion—large northward displacement since Early Paleocene time—is of critical importance in later discussions.

**Nowitna Lava Flows, McGrath Region**

Almost 800 km (500 mi) north of the Kodiak Island sites (Fig. 1, no. 3), we conducted a pilot study on andesitic lava flows of the Paleocene Nowitna Volcanics exposed in the Nixon Fork–Innoko terranes (Plumley, 1984). In this region, the Nowitna Volcanics give K–Ar ages of about 64 Ma (Moll et al., 1981) and overlap both the Innoko and Nixon Fork terranes (Fig. 1). In a broader sense they belong to the Kuskokwim Mountains magmatic belt of Late Cretaceous to Early Tertiary age, which extends from...
# Table 1

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ID No: Same numbers as for Table 2 and Figures 1 and 2; AGE: K–Ar dates on flows or associated igneous rocks, except for no. 5 (see text); N/N₀: Number of sites used in analysis/total number of sites; POL: Polarity (Normal sites/Reversed sites); COORD: Geographic (in situ) or Stratigraphic (structurally restored) coordinates; Directions: Mean of characteristic (most stable) site mean directions, with reversed polarity inverted to normal—D = declination, I = inclination, α₉₅ = radius of 95% confidence circle, k = precision parameter; POLES: Paleomagnetic pole obtained by averaging VGP's derived from such site mean directions (see Appendix A)—φ = E. long., λ = N. lat., A₉₅ = radius of 95% confidence circle, K = precision parameter.  
⁺One tuff unit excluded from N₀.  
³Six tuff units and one sedimentary unit excluded from N₀.  
²Single date with unusually large error bars (±13 Ma).

Table 1—Summary of latest Cretaceous and Early Tertiary paleomagnetic results from UCSC lab.

The Bering Sea in the southwest to at least as far as the Kaltag fault in the northeast (Moll and Patton, 1982; Wallace and Engebretson, 1984). In the area that we were able to reach (Fig. 1, no. 3) the exposures were not extensive, despite the considerable thickness of the section, with the result that only seven flows could be sampled. For the most part, attitudes had to be estimated from hillside benches that formed on top of the more erosion-resistant flows. Fortunately, dips were gentle, and the flows were essentially unmetamorphosed.

Large scatter in the direction of natural remanent magnetization (NRM) and occasional exceptionally strong intensities indicated overprinting induced by lightning. Demagnetization in alternating fields ranging from 200 to 500 Oe effectively removed this random overprint well enough to estimate a characteristic component in all but a few of the most intensely magnetized samples. This characteristic component is reversed in every case. Thermal demagnetization, which was employed in some samples, showed that it is carried by both magnetite and hematite. Thus, even though no fold or reversal test is available, the characteristic remanence is very probably primary.

Six of the flows give mean directions (Table 1, no. 3) that cluster relatively near the expected Paleocene field direction for their location. The flow mean for the seventh was not included with the others because it is transitional between reversed and normal polarity, about 90° away from the mean of the other six. Because no other reason for this discrepancy is apparent, we think it was erupted during a geomagnetic excursion (see, for example, Doell and Dalrymple, 1973). Such large excursions of field direction are thought to require at least a few hundred to a thousand years to happen. Moreover, the directions of the other flows that lie under and over it do not show significant serial correlation. Therefore, the flows probably span at least 2,000 years, enough to provide a fair sampling of secular variation (Champion, 1980). In contrast to the results from Kodiak Island, the mean direction is consistent with little or no latitudinal displacement and rotation relative to North America (Table 2). The 95%
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<td>O,P</td>
<td>16*</td>
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<td>E,L</td>
<td>-</td>
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ID NO: Study identification number, same as used in Figures 1 and 2 and Table 1. Age: Approximate age of rocks studied, determined by K-Ar method or (when in parentheses) assigned on basis of paleontological and geological evidence. Ref: A. Hillhouse and Grommé (1983a); B. Hillhouse et al (1983); C. Hillhouse and Grommé (1982); D. Plummer (1984); E. Stone et al (1982); F. Globberman et al (1983); G. Globberman and Grommé (1983 and in preparation); H. Thrupp and Grommé (1983, 1984); I. Stone (1983); J. Packer (1972); K. Stone and Packer (1977); L. Stone and Packer (1978); M. Hillhouse and Grommé (1977); N. Grommé and Hillhouse (1981); O. Plummer et al (1983); P. Plummer et al (1982); Q. Panuska (1983). Italics indicates source for quantitative paleomagnetic data actually used in table. Reliability Factors: + or − indicates factor is affirmative (positive) or negative, respectively; a blank indicates no information regarding the factor. LF, lava flows sampled; N, number of samples used or, when asterisked, number of sites used (average usually 3 to 7 samples per site); K/Ksv, precision parameter for data/precision parameter for secular variation appropriate to the paleolatitude; AF, alternate field demagnetization used; TH, thermal demagnetization used; VC, some form of vector component analysis used; RT, reversal test passed; FT, fold test passed. PLAT: Paleolatitude and 90% confidence limit inferred from mean paleomagnetic direction. DISPL and ROT: Displacement northward (+) or southward (−) and azimuthal rotation clockwise (+) or counterclockwise (−) of sampling area with respect to cratonic North America, inferred from the difference between the mean paleomagnetic pole and the coeval North American reference pole. Uncertainties are 95% confidence limits estimated by the method of Demarest (1983) outlined in the Appendix.

*Stepwise thermal demagnetization conducted on pilot samples from each flow, confirming that the characteristic direction is essentially the same as that obtained by AF demagnetization (J. W. Hillhouse, personal communication).

This result is now considered invalid because of previously unrecognized overprintng (D. B. Stone, personal communication).

Examination of original data listing (ref. K, Table 2, p. 192) shows that the directions fail the fold and reversal tests. Hence the results given in ref. E and this table are not valid.

Two-level analysis conducted on samples from pillow basalt and dikes in one area and dikes in another area. N and K not comparable with those of usual single-level analysis (J. W. Hillhouse, personal communication).

Table 2—Tectonopaleomagnetic data summary for southern, southwestern and central Alaska from Late Cretaceous to Present.
confidence limits, however, are large because of the small number of flows sampled.

**Unnamed Lava Flows, North Bristol Bay**

In the Togiak terrane (Fig. 1, no. 6), more than 600 km (373 mi) to the southwest of the Nowitna Volcanics sampling area, at the southwesternmost extremity of this same Kuskokwim Mountains magmatic belt, we collected about 700 samples from 91 subaerial volcanic flows and pyroclastic deposits on Hagemester, Crooked, and Summit Islands in northern Bristol Bay for a detailed paleomagnetic study (Globerman and Coe, 1983, and in preparation). This volcanic sequence, which is well exposed along the shorelines, comprises mainly basaltic-andesite flows interbedded with airfall tuff, fine-grained sediments, and volcanic breccia. The sequence is homoclinically dipping 65 to 75° toward the southeast on Hagemester Island, but on Crooked and Summit Islands the dips are shallow. Their chemistry is consistent with a volcanic arc setting (Globerman et al, 1983). K-Ar dates on three of the flows give a mean age of 68 ± 3 Ma.

These samples were magnetically straightforward. Both alternating field (AF) and thermal stepwise demagnetization experiments were analyzed with vector diagrams for about half of the samples to isolate a characteristic component. A stable endpoint, that is, a univectorial decay toward the origin, was achieved in almost every case by 200 Oe or 400° C (752°F). Blanket treatment at one or two alternating field values or temperatures was employed on the other half of the samples. AF and thermal methods were equally successful, except for a small fraction of samples in which thermal demagnetization was necessary to remove a secondary overprint carried by hematite. Again, the characteristic component carried by magnetite and hematite was the same, which is consistent with our hypothesis that the hematite originated by auto-oxidation processes (Wilson and Haggerty, 1966; Grommé et al, 1969) during primary cooling.

The mean directions of six coarse-grained tuffaceous deposits and one sedimentary interbed were considered unreliable and were discarded. In addition, the results from ten lava flows with strongly discrepant directions (VGP's more than 50° from the mean) were eliminated. These discrepant directions, which occur in a few flows from two sections within the volcanic sequence on Hagemester Island, show strong serial correlation and are statistically distinct from the near-Fisherian distribution defined by the directions of the remaining 74 flows. They have almost certainly recorded two geomagnetic excursions and should be eliminated in order to obtain the best estimates of paleolatitude, poleward displacement, azimuthal rotation, and their uncertainties (e.g., see Harrison's [1980] careful analysis of results from more than 1,000 lava flows in Iceland).

The remaining 74 sites all have unambiguous normal polarity. Thick, well-laminated sedimentary interbeds indicate, however, that the flows span a period sufficiently long to obtain a representative time average of the ancient field. Since there were several periods of normal polarity in Maastrichtian and early Paleocene time lasting 0.5 to 1.0 m.y. (Harland et al, 1982), it is not unlikely that the entire sequence accumulated within one of them. The interbeds also give us confidence in the structural attitudes that we determined. Rotation of the flow mean directions into stratigraphic coordinates using these attitudes yields a strongly positive fold test (McFadden and Jones, 1981), significant at the 95% confidence. Despite the lack of a reversal test, we are confident that the characteristic component is primary.

The inclination of the mean characteristic direction for the 74 flows is close to the expected value for latest Cretaceous time, but the declination is significantly rotated in a counterclockwise sense. Thus, little northward displacement (9 ± 7°) with respect to North America is indicated, but there is a strong suggestion of counterclockwise rotation (43 ± 23°). Note that if the ten directions discarded because they were thought to reveal field excursions had been retained, these mean values would have been little changed: 6 ± 7° and 47 ± 25°. Because the remanent magnetization is simple and stable, the structural corrections are unusually well determined, the number of flows is large, and the period of time they span appears to be relatively long, we believe the results of this study are particularly reliable.

**Unnamed Tuffaceous Rocks, Lower Yukon River**

Globerman et al (1983) came to a similar but much less well-constrained conclusion in their paleomagnetic study of beds of tuff and tuffaceous sediment exposed along the Yukon River about 300 km (186 mi) north of the Bristol Bay area (Fig. 1, no. 5). These rocks (Hoare and Coonrad, 1959; Hoare, 1961), which are part of an uppermost Jurassic to Lower Cretaceous belt of andesitic flows and volcanioclastic rocks that characterize the Yukon-Koyukuk province in the northeast (Patton, 1973), belong to the Koyukuk terrane of Jones et al (1984). In the study area, bedding attitudes vary by about 30°, enough to allow application of a weak fold test. Of 109 samples collected at 31 sites spanning about 1.5 km (0.9 mi) stratigraphic thickness, 87 (27 sites) yielded useable estimates of characteristic direction in thermal and AF demagnetization experiments (Table 1). All sites have normal polarity, and the scatter in directions increases slightly when the structural correction is applied. A few samples, however, revealed a reversed characteristic direction, usually after removal of a heavy normal component at lower temperatures or alternating field strengths. For all these reasons, we interpret the characteristic remanence to be a secondary overprint.

The age of the overprint is problematic. We have used 70 Ma because peak activity in the Kuskokwim Mountains magmatic belt appears to have occurred then (Wallace and Engebretnson, 1984, Fig. 4). Assuming the beds have not been tilted since overprinting, the paleomagnetic results in geographic coordinates imply little or no northward displacement (7 ± 10°) but strong counterclockwise rotation (77 ± 37°) relative to the North American craton (Table 2). These conclusions, however, are sensitive to the exact assumptions. For instance, if the age of remagnetization was older, say between 90 and 120 Ma, the calculated displacement increases to about 12° and the rotation decreases to about 50°. If 30% of the average tilt of the beds occurred after the postulated 70 Ma remagnetiza-
tion event, the values of displacement and rotation would both be cut roughly in half.

**Unnamed 66 Ma Lava Flows, Lake Clark Area**

About 400 km (249 mi) to the southeast, just northwest of Lake Clark, we sampled 30 andesite flows (Fig. 1, no. 7). According to the latest version of the Alaska terrane map (Jones et al., 1984), these lie on the Jura–Cretaceous flysch terrane that separates the southern terranes from the rest of Alaska. One flow has a rather poor K–Ar age determination of 66 ± 14 Ma, which suggests that these flows belong to the Alaska Range magmatic belt (Hudson, 1979; Wallace and Engebretson, 1984). Dips are shallow (less than 20°) to the southwest and poorly defined, so a conclusive fold test could not be obtained.

Preliminary results of this study have been given by Thrupp and Coe (1983), and a more detailed account is now in preparation. For the most part, isolation of a characteristic component by either thermal or alternating field demagnetization was straightforward. The less stable component that was removed appeared to be recent field viscous remanent magnetization (VRM) in some cases and lightning-induced isothermal remanent magnetization (IRM) in others. Five of the flows are reversed, with directions nearly antipodal to those of the other 25 flows. Thus, it is very likely that the characteristic component is primary and that enough time is spanned by these samples to provide a good time average of the ancient field. The mean direction in stratigraphic coordinates (Table 1) has inclination fairly close to that expected using the 65 Ma North American reference pole (Table 4), but the declination is again rotated counterclockwise. This corresponds to a modest northward displacement (11 ± 9°) and a sizeable counterclockwise rotation (52 ± 22°) relative to cratonic North America. Using either the 55 Ma or the 75 Ma reference pole does not significantly affect these conclusions.

**Unnamed 44 Ma Lava Flows, Lake Clark Area**

Some 40 km (25 mi) to the northeast of the 66 Ma sequence (Fig. 1, no. 8), we sampled 7 lava flows spaced through a series of 15 to 20 flows that dip about 25° to the east (Thrupp and Coe, in preparation). These have a K–Ar age of 44 Ma, suggesting that they represent early activity of the onland extension of the Aleutian arc (Wallace and Engebretson, 1984). All but one of these flows were also cleaned of minor secondary components of VRM and IRM. The six remaining flows are reversed with a mean direction close to that expected for their age (Table 1). Little or no northward displacement and counterclockwise rotation is indicated (Table 2), but the uncertainty is large because the number of flows is few and there is no independent assurance that a good time average of the ancient field has been obtained.

**Summary**

The poleward displacements and rotations inferred from our work are depicted graphically in Figure 1. Five results concur that the terranes north of the Peninsular terrane have undergone at most a modest latitudinal displacement during Tertiary time. They also suggest the possibility of systematic counterclockwise rotation. In contrast, the Kodiak Island study suggests that the Prince William terrane has undergone a substantial northward displacement of 25 ± 7° and is characterized by inconsistent azimuthal rotations. No direct information was obtained from the Chugach and Peninsula terranes, which lie between our northern and southern paleomagnetic data sets. However, the distinctive plutons of the Gulf of Alaska magmatic belt (Hudson, 1979; Hill et al., 1981; Moore et al., 1983; Wallace and Engebretson, 1984) provide a loose tie between the Prince William and Chugach terranes, and apparently to the southernmost Peninsula terrane as well (Davies and Moore, 1984). Taken at face value, these ties suggest that the southern part of the Peninsula terrace has also moved north with the Prince William terrane. We will return to this subject in the section entitled Proposed Scenario.

**PALEOMAGNETIC DATA SUMMARY**

In this section we examine these tentative conclusions in the context of other paleomagnetic data available in the literature. We convert these data (including our own) to the tectonopaleomagnetic parameters of interest—paleolatitude, latitudinal displacement, and azimuthal rotation—and summarize them in Table 2. Because the intrinsic quality can vary, we discuss below factors that affect the reliability of paleomagnetic data. Much of this can be skimmed by practitioners of paleomagnetism. The eight columns in Table 2 under the heading Reliability Factors, as well as the 95% confidence limits, provide the basis for a rudimentary evaluation that is key to the discussion that follows.

**Reliability Factors**

We take these reliability factors under the general categories of confidence limits, rock types, sampling, demagnetization, and stability tests. We include a selective review of basic material that, in our opinion, is essential for a critical evaluation of the discrepancies in the paleomagnetic data from Alaska.

**Confidence Limits**

Random errors accumulate during all phases of collecting, measuring, and magnetic cleaning. In addition, natural causes of error usually have a random component. Such errors contribute to the scatter of sample directions and so are naturally accounted for in the estimate of confidence limits. Systematic errors, however, are not. Thus the confidence limit that is listed with each value of paleolatitude, latitudinal displacement, and azimuthal rotation in Table 2 is only one of several factors that contribute to the reliability of a result.

**Rock Types**

The reliability of paleomagnetic results depends directly on the fidelity with which rocks record and preserve the ancient field direction and on the accuracy with which structural tilting can be identified and corrected for. It is not surprising that rocks differ in these regards. Lava flows and near-shore clastic sediments are the rock types from
which almost all the paleomagnetic results listed in Table 2 have been derived.

Lava flows are probably the most faithful class of paleomagnetic recorders commonly available in nature. Experiments have repeatedly demonstrated that most lava samples acquire a TRM during cooling that is parallel within 1 to 2° to the ambient magnetic field. Such TRM is usually strong and stable (especially those that have undergone auto-oxidation), and the mechanism by which it is acquired is relatively well understood (e.g., Nagata, 1961). For these reasons, we have indicated in the column headed LF (lava flow) in Table 2 whether or not the paleomagnetic result was derived from lava flows.

Sediments, on the other hand, may acquire their primary (or quasi-primary) remanence by a variety of mechanisms (e.g., Verosub, 1977; Tucker, 1983a). The fidelity with which they record the ambient field direction will depend on the mechanism or combination of mechanisms involved. Most of these are poorly understood, and it is very difficult, especially with shallow-water clastic sediments, to establish which mechanisms have operated in any given case. Depositional remanent magnetization (DRM) produced by redepositing varved lake sediments in the laboratory suffers from a systematic inclination error (King, 1955; Griffiths et al., 1960). The inclination of DRM in the redeposited sediments is too shallow by an amount that depends on the inclination of the field, ranging from 0 to values typically as high as 25° (Fig. 3). Paleolatitudes derived from such DRM would be systematically low, the error reaching a maximum of 25° at a true latitude of 58°. In naturally deposited varved lake sediments, evidence has been found also for inclination errors that vary from one-quarter to two times the experimental values depicted in Figure 3 (Ising, 1942; Johnson et al., 1948; Griffiths, 1955; Graner, 1958). The mechanism responsible appears to be mechanical rotation of the magnetic grains upon impact with the water-sediment interface (King, 1955; Griffiths et al., 1960).

Fortunately, in many types of sediments the remanence is not locked in until some time after deposition. Such post depositional remanent magnetization (PDRM) is not susceptible to the inclination error that may result from the process of deposition (Irving and Major, 1964). The lack of systematic inclination error has been particularly well documented for deep-sea sediment cores (Opdyke and Henry, 1969). In such sediments low deposition rates, fine grain sizes, and intense bioturbation may promote the acquisition of PDRM. Alternatively, if the remanence resides in biogenic magnetite derived from organisms that lived in the bottom mud (Kirschvink, 1983), it would be postdepositional by definition. The precise factors are probably complex and are not well understood. For example, Tucker (1983b) has described a case in which the remanence of carbonate ooze was reset by slumping while the remanence of nearby clay-rich sediment involved in the same slump was unaffected.

In addition, the large uniaxial compaction that is experienced by some sediments, to the extent that it occurs after PDRM lock-in, would be expected to cause inclination error by rotating the magnetic grains (Blow and Hamilton, 1978). The effects of this mechanism would be more pronounced in dry outcrop samples than in saturated, incompletely compacted core samples. This mechanism has been suggested in explanation of average inclination shallower than that of the axial geocentric dipole field that has been observed in outcrop samples of Mono Lake sediments (Liddicoat and Coe, 1979). The shallowing of inclination by compaction should exhibit the same sort of dependence on field inclination as the depositional inclination error. In the extreme case, where all magnetic grains are so inequent that they rotate as homogeneous strain markers, a 60% compaction after lock-in of PDRM would produce the same inclination error as that illustrated in Figure 3. Compaction error, however, probably does not affect sediments that are cemented before the accumulation of a significant overburden, such as many limestones.

At the present time there are no widely accepted criteria for predicting inclination error, especially in coastal and marginal sea sediments. Simpson and Cox (1977) obtained essentially the same average direction both from fine-grained layers of the turbidite Tyee Formation in western Oregon and from sequences of lava flows that immediately overlie and underlie the Tyee, thereby demonstrating the absence of significant inclination error. Thompson and Kelts (1974), however, found significantly shallower inclinations in the coarser parts of turbidite layers than in the finer grained, laminated parts. Nonetheless, fine grain size is not a guarantee against inclination error. Blow and Hamilton (1975) showed that the inclinations of DSDP sediment cores from the Arabian Sea were much more consistent with those expected from the northward movement of India if a correction for inclination error was applied to those that were deposited more rapidly than 700 m/Ma (2,297 ft/Ma). A similar example can be cited of probable inclination error in the fine-grained, laminated lutite core studied by Creer (1974). The average inclination of sediment spanning approximately 5,000 to 25,000 years B.P. is about 15° shallower than that of an axial, geocentric dipole field, whereas the average inclination during the same period found in a core from the Aegean Sea less than 1,500 km (932 mi) away shows no significant discrepancy (Opdyke et al., 1972). Finally, Alvarez and Lowrie (1984) demonstrated the absence of significant inclination error in white, calcareous turbidites from Italy. This result held true for both coarse- and fine-grained portions of the turbidite units. The authors point out that this might be expected for calcareous turbidites because the magnetite grains are exceedingly small and thus easily rotated within larger, water-filled pores of the matrix by Brownian movement after deposition.

In summary, although little is known of a systematic nature about the frequency and magnitude of inclination error in near-shore environments, we consider it to be a real danger. Sandstones and coarse siltstones are probably most prone to deposition-induced inclination error. Clay-rich sediments are probably most susceptible to compaction-induced inclination error. In the absence of deeper understanding, we regard tectonic conclusions derived from the inclination of such sediments with caution. On the other hand, we generally expect the mean declination to be recorded more faithfully, except in regions of strong,
systematically directed bottom currents (King, 1955).

Conversely, more reliable structural corrections can generally be made on sediments than on lavas, for two reasons. First, the orientation of sedimentary bedding can usually be measured more precisely than the orientation of the top or bottom of a lava flow. Second, the risk of substantial initial dip is greater for lava flows than for most sedimentary rocks. Thus, structural corrections of lava flows to paleohorizontal are likely to be more reliable when attitudes are obtained from sedimentary interbeds than from the flows themselves, as is the case for several of the studies listed in Table 1. In the absence of sedimentary interbeds, a typical value for the error in structural correction expected for a single flow is around 5°. These errors, however, will tend to average out when there are a number of sites distributed over a large area.

**Sampling**

Reliable tectonic application of paleomagnetic data also hinges on the assumption that the geomagnetic field closely approximates the field of an axial geocentric dipole when averaged over a suitably long period of time. Except during
episodes of unusual field behavior such as reversals and excursions, this assumption appears to be generally true within a few degrees (e.g., McElhinny and Merrill, 1975). Analysis of archeomagnetic data suggests that a period of 2,000 years or so may be a sufficiently long time average (Champion, 1980), although one would feel more comfortable with an averaging time at least several times this figure. If the ancient field is sampled over too short a period, the mean paleomagnetic pole position will not usually provide a good approximation of the paleogeographic pole because the effects of nondipole and nonaxial dipole fields will not have been averaged out.

Often it is difficult to know whether a representative time average has been obtained, especially for a result in the literature about which little detailed information is given. To answer this question rigorously one would need a realistic model of paleosecular variation and knowledge of the number of samples, the length of time they span, and their distribution within this time span. If, however, the precision parameter (Fisher, 1953), $K$, of a set of paleomagnetic data is significantly greater than that expected at that paleolatitude because of secular variation alone, $K_{SP}$, then one would strongly suspect that the sampling interval was too short (e.g., Cox and Gordon, 1984). This test is shown in Table 2 in the column headed $K/K_{SP}$, where $K_{SP}$ has been taken from Harrison's (1980) model of secular variation. The great majority of the studies have $K/K_{SP}$ values that range between 0.4 and 0.8, leaving a comfortable margin for the inevitable scatter resulting from experimental and natural causes of error. Only three studies have values greater than 1.0. One of these (no. 22) stands out from the rest with a value of 4.4, indicating that the remanence of all these samples was probably acquired within an interval of time that is short compared to the dominant periods of secular variation. This might be due to a chemical remanent magnetization (CRM) overprint or to sampling within a very restricted stratigraphic interval.

The number of sites (i.e., distinct time horizons) that constitute a paleomagnetic study, given in the column headed $N$ in Table 2, can also give some indication of the overall reliability of the result. If $N$ is too small, then, no matter whether the sites are well distributed throughout a long interval of time, the confidence limits will be unacceptably large. For example, to achieve a definitive result we would like to keep the contribution of secular variation to the 95% confidence circle about the mean pole to 5° or less. Using Harrison's (1980) model for secular variation, we find that a minimum of 22 sites would be required if the paleolatitude were 0°, 40 sites if the paleolatitude were 45°, and 55 sites if the paleolatitude were 90°. If a 10° confidence circle were acceptable, the minimum number of sites needed ranges from 7 to 15. In practice, particularly in the case of lava flows, sites may be bunched temporally, so that more than the minimum number would be needed (Cox and Gordon, 1984).

It should be pointed out that the number of sites, $N$, in Table 2, is equal to the number of samples for the paleomagnetic studies of sedimentary rocks, whereas for the lava flows an average of at least six samples per flow were employed to determine each site mean direction. The only exception is study no. 5, on tuffaceous rocks, in which an average of three samples per site was used. The statistical effect of taking the mean of multiple samples per site is to reduce scatter arising at the within-site level, thereby improving the overall precision. Comparing results for more than one sample from the same site also helps catch orientation mistakes that might otherwise propagate into the site mean. In addition, knowledge of the scatter about each site mean provides an objective basis for eliminating aberrant site directions from the overall mean.

Demagnetization

Demagnetization experiments are essential in paleomagnetic studies. This is especially true in tectono-paleomagnetic investigation of terranes, where the variety of rock types available to work with is often severely limited. A well-designed demagnetization procedure has a hierarchy of goals: (1) to establish the presence or absence of more than one component of remanent magnetization, (2) to determine the direction of each component, and (3) to provide information that aids in identifying the age and probable origin of each component. The characteristic (most stable) component is generally of greatest importance, but the properties of the less stable components are often useful in deciphering the history of the rock and in deciding whether the characteristic component is primary.

The columns headed AF and TH in Table 2 show whether alternating field and thermal demagnetization experiments were used successfully (+), were tried but were not successful (−), or were either not tried or not reported (blank). AF demagnetization is optimal for removing IRM overprints, for example, as caused by lightning strikes, and it is often satisfactory for dealing with the VRM induced at room temperature in magnetite, also. Thermal demagnetization is optimal for removing all types of VRM and partial TRM overprints, which are collectively referred to as VPTRM (the partial TRM acquired by cooling from some temperature in a magnetic field plus the VRM acquired as a result of being held at elevated temperature for an extended period of time). Thermal demagnetization probably holds the edge for removing most types of CRM, whereas AF demagnetization has the advantage that it can be used on materials that cannot stand heating. Thus, it is much more likely that overprints will be detected and completely removed if both types of demagnetization have been tried, and the best one (or combination) selected empirically. For example, in studies 20 and 21 in Table 2, a large secondary component, presumably VPTRM, is effectively removed from the characteristic component by thermal demagnetization, whereas with AF demagnetization it is not even detectable (Plumley et al., 1983). Conversely, we generally find that thermal demagnetization does a poor job of removing IRM and sometimes fails even to detect it.

Except for straightforward samples with minor overprints, stepwise demagnetization that removes remanence of progressively higher stability combined with some form of vector component analysis is generally more effective than demagnetization at one or a few blanket values and plotting the directions on an equal area net.
Many variations of such vector component methods have been presented and used to very good effect (Zijderveld, 1967; Halls, 1978; Hoffman and Day, 1978; Kirschvink, 1980). These methods allow one to discriminate better whether or not two or more components of remanent magnetization have been cleanly separated and to determine their directions more precisely. Thus, in Table 2 studies that are known to have employed vector component analysis are marked with a + in the column headed VC.

Stability Tests

One of the greatest pitfalls in the application of paleomagnetism to the tectonics of terranes is mistaking secondary characteristic remanence for primary. Demagnetization experiments provide no clues for recognizing when the primary remanence has been completely replaced by a secondary overprint, unless the overprint is carried by a mineral that is known to be secondary and that has magnetic properties that make it easily identifiable (e.g., goethite). If the overprinting postdates significant latitudinal displacement, azimuthal rotation, or simple tilting of the rocks, misinterpretation of the characteristic remanence as primary will result in serious errors in tectonic reconstructions. Fortunately, a number of stability tests exist that can guard against such errors (e.g., McElhinny, 1973). Two of these, the reversal and fold tests, have been applied successfully in some of the studies listed in Table 2.

If paleomagnetic study of a suite of samples from a formation reveals characteristic remanence of reversed polarity in some time-stratigraphic zones and normal polarity in others, it is likely that the characteristic component is primary. Otherwise, quite special circumstances would have to be invoked to explain this occurrence by secondary overprinting. If analysis shows that the angle between the mean normal and mean reversed directions is not significantly different from 180°, then it is even more probable that the characteristic remanence represents a primary recording of the geomagnetic field. Moreover, since the geomagnetic field takes a few thousand years to reverse, a positive reversal test demonstrates that the samples span an interval at least that long, a point that is often not easy to establish by other means if the units sampled are lava flows. Finally, when the normal and reversed components can be shown to be closely antiparallel, it provides assurance that the characteristic direction determined in that study is not significantly contaminated by residual secondary components. In Table 2, a + in the column headed RT denotes a positive reversal test, a − denotes a negative reversal test—i.e., normal and reversed directions significantly different from antiparallel—and a blank indicates that no reversal test was available or reported.

The other very useful test is the fold test, of which several versions exist (Graham, 1949; McElhinny, 1964; McFadden and Jones, 1981). All depend on the same principle that, if secondary remagnetization postdates significant folding, applying the various structural corrections to characteristic directions of the samples should increase their scatter. In such case the directions are said to fail the fold test, a result which is indicated in Table 2 by a − in the column headed FT. Conversely, if the directions converge convincingly on structural correction, the characteristic remanence probably predates all or most of the deformation and the fold test is termed positive (denoted by a + in Table 2). When enough variability in structural attitudes is available to provide a good test, a positive fold test is therefore a necessary but not a sufficient condition for the characteristic remanence to be primary. The fold test can also be inconclusive if the various samples were remagnetized at different times throughout the period of folding. A blank in the appropriate column of Table 2 indicates that the fold test was inconclusive, not available, or not reported.

Despite the ambiguities that sometimes arise, the fold test is extremely valuable in many instances. A convincingly negative fold test is virtually conclusive proof that the characteristic remanence is not primary. When the age of folding and other aspects of the geological history of the rocks are known, a convincingly positive fold test often constitutes strong evidence that the characteristic remanence is primary.

Evaluation

All the paleomagnetically inferred latitudinal displacements and azimuthal rotations contained in Table 2 are depicted graphically in Figure 2, with the exception of one result (no. 4, Table 2) that has been omitted for reasons given below. The general pattern of displacements is qualitatively similar to those shown by our own data in Figure 1: large northward displacements of the southern terranes and no significant displacements of the northern terranes. In detail, however, the picture is badly blurred by systematic inconsistencies between the displacements determined from lava flows and sediments. This can be seen at a glance in Figure 2, where displacements obtained from lava flows are much less than those obtained from sediments of comparable age. Table 3 shows a quantitative comparison, mainly for rocks ranging in age from 60 to 75 Ma. For the Prince William and Chugach terranes considered as a unit (Moore et al., 1983), the average displacement inferred from lavas is less than half that inferred from sediments (24 ± 4 versus 54 ± 6°, respectively). In the “northern” terranes (north of the Peninsular terrane), displacements derived from six different studies of lava flows, including four with dates from 60 to 68 Ma, all indicate at most a rather modest latitudinal displacement, whereas a surprisingly large displacement of 67 ± 7° was inferred from a study of clastic sedimentary rocks that are only 20 m.y. older (no. 4, Table 2). Further analysis of results from rocks in this latter area, however, has shown that the characteristic remanence, once thought to be primary, is probably a secondary overprint (D. B. Stone, 1983, personal communication), thereby invalidating the large displacement inferred above.

It is worth inquiring, therefore, whether any other of the studies with anomalously large displacements listed in Table 2 might also suffer from the problem of secondary remanence that has been incorrectly interpreted as primary. Reanalysis of the data given in the original publication for study no. 18 (Table 2) reveals that they fail the fold test. Moreover, even though both polarities are present, the normal and reversed directions are much more nearly
antiparallel in geographic than in stratigraphic coordinates. This is strong evidence that the remanence is secondary, despite the fact that a reversal was recorded. There are 16 additional results listed in Table 2 for which no fold test or reversal test is available. These include all but one of the studies with anomalously large northward displacements. As already mentioned, one of these (no. 22, inferred northward displacement of 60°) has a very large value of \( K \), 4.4 times that expected for secular variation at the paleolatitude calculated from its mean direction. Overprinting could easily account for the anomalously large values of both \( K \) and displacement. There are other possible victims of overprinting; for instance, no. 26 (Table 2, apparent poleward displacement 68°). This study has a value of \( K/K_{0} = 1.5 \) and a structural correction of more than 50° that drastically shallows the inclination. These examples underscore the need for using stability tests to check for remagnetization.

It is most improbable, however, that undetected secondary characteristic remanence can explain all the instances in Table 2 of surprisingly large northward displacements. Among those for which no fold or reversal test is available there are several (nos. 11–15, 23, and 24) for which the direction of in situ remanence is so shallow or the structural correction is so small that post-tilting acquisition of a steeply dipping overprint cannot possibly account for the anomalously low paleolatitude. Moreover, there is one (no. 9, Chickaloon Formation, Matanuska Valley) that passes both local and regional fold tests and the reversal test (Stone, 1983). The inferred northward displacement is 48° since Paleocene time, which is 23° greater than that deduced from lava flows and dikes of similar age from the Chugach and Prince William terranes (no. 19, 20, and 21, Table 2). This large displacement appears excessive, particularly because these latter terranes lie outboard of the Matanuska Valley. A possible explanation of this and other systematically low paleolatitudes in Table 2 inferred from paleomagnetic studies of sediments is inclination error, as discussed earlier. Using the typical values shown in Figure 3 of inclination error found in experiments and in natural settings for clastic sedimentary rocks, we find that the apparent paleolatitude of 22°N deduced from the observed paleomagnetic inclination of the rocks would correspond to an actual paleolatitude of 45°. This adjusted value is in excellent agreement with the mean for the three studies to the south just mentioned. For the same reasons, we would guess that the paleolatitude of 32° deduced from sandstone of latest Cretaceous age on Wrangellia (Table 2, no. 28) is somewhat too low. Using the simple adjustment for inclination error, a value of 57° is found, which is only 6° higher than the paleolatitude of coeval igneous rocks immediately outboard in the Chugach terrane. Similarly, the anomalously low paleolatitude inferred from the Ghost Rocks Formation sediments (no. 23, Table 2) adjusts to 43°, only 3° more than the mean derived from the Ghost Rocks volcanics. It is also interesting and perhaps significant that the declinations of the sediments and the nearest lava flows (Kiliuda Bay, Table 1) agree within 4°. This agreement is consistent with the hypothesis of depositional or compactional inclination error. Finally, the adjusted paleolatitudes for no. 24 and for the mean of nos. 10 to 15 (70 to 85 Ma sediments of the Peninsular terrane) are also quite reasonable, though individually quite scattered in the latter case.

In summary, the paleomagnetic results in Table 2 derived from lava flows appear much more reliable than those derived from sediments. Not only are lava flows generally better recorders than clastic sedimentary rocks, but the lava flow studies were much more thorough than all the sediment studies with the exception of nos. 5 and 9. In contrast to the studies of sediments, all but two of the studies of lava flows employed at least some stepwise thermal cleaning in addition to AF cleaning and used some form of vector component analysis to extract the characteristic remanence. All but two were backed up by a positive fold test, reversal test, or both. Thus, the results derived from lava flows are highlighted in bold face on the map in Figure 2.

The results from the studies of sedimentary rocks are systematically biased toward shallow inclinations and, therefore, low paleolatitudes and large northward displacement. Undetected secondary overprints and inclination errors appear capable of explaining perhaps all of these discrepancies. Again, however, it should be noted that several paleomagnetic studies from fine-grained turbidites suggest that these rocks have faithfully recorded the geomagnetic field direction and are therefore free of inclination error. Declination is not affected by the processes responsible for inclination error, so that these results may be more useful for indicating azimuthal rotations than they appear to be for determining northward displacements.
Discussion

Northern Terranes

The paleomagnetically inferred latitudinal displacements for the terranes to the north of the Peninsular terrane are modest in magnitude and divided almost equally between positive (northward) and negative (southward). These include six results from lava flows and one from tuffaceous sediments. The eighth result indicating a large displacement (no. 4, Table 2) is not considered valid, as discussed previously. The apparent displacements range from $-9$ to $+11^\circ$, with the negative values lying to the east of the positive ones (Fig. 2). We are uncertain, however, whether any of these values are significantly different from zero.

Three of the displacements appear to be statistically significant at marginally greater than 95% confidence (nos. 2, 6, and 7, Table 2). It is important to note, however, that the formal confidence limits are always minimum estimates for two reasons. First, they are often based on overestimates of the number of independent samplings of the geomagnetic field, especially in the case where a sequence of lava flows is sampled (e.g., Cox and Gordon, 1984). Preliminary analyses of the sequences of directions suggest that the overestimate is roughly a factor of two, which implies that the confidence limits given for them in Table 2 are too small by a factor of about 1.4. Second, as mentioned earlier, the formal confidence limits do not take account of possible sources of systematic geological errors. The most serious of these for lava flows is usually uncertainty in the structural correction. For example, typical initial dips for lava flows on the flanks of shield volcanoes are 5 to 7°, and they may be considerably steeper than this. Such initial dips are difficult to distinguish in ancient environments from tectonic dip and thus undoubtedly lead to spurious estimates of latitudinal displacement. Since 5° error in inclination corresponds to 8 or 9° of apparent latitudinal displacement at the high paleolatitudes of these studies, it is entirely possible that any one of all the paleomagnetically inferred displacements that appear statistically significant are artifacts of the initial dip.

Averaging the results of various studies spread over a sufficiently wide area should lessen the effects of initial dip. To avoid the possibility of subconsciously biasing the results, we have treated the question of initial dip uniformly by structurally correcting beds to the horizontal in all studies regardless of whether their dips were steep or shallow. In other words, we take the initial dip to be zero in all cases and assume that the errors involved will tend to average out. The average displacement for the four studies of lava flows with ages between 60 and 68 Ma (Table 2, nos. 2, 3, 6, and 7) is 2° northward, with a standard error of 5°. Inclusion of two results from younger flows (nos. 1 and 8), with ages of 52 and 44 Ma, respectively, changes this figure to $0 \pm 3^\circ$ northward. Finally, if we include the direction derived from remagnetized tuffaceous sediments (Table 2, no. 5), we still get only $1 \pm 3^\circ$ of northward displacement.

We conclude that the mean displacement of the terranes north of the Peninsular terrane since latest Cretaceous time is not significantly different from zero and that therefore the modest displacements found by us and others in individual studies might not be real. The fact that the northward and southward apparent displacements found so far group to the west and east, respectively, could be used as an argument against this latter interpretation. Further studies are needed to resolve this second-order problem.

The azimuthal results for the northern terranes (Fig. 2) show a distinct counterclockwise bias. The only exception is the small clockwise rotation of $5^\circ$ indicated by the Nowitna Volcanics (no. 3, Tables 1 and 2). This determination has the largest error of all the lava flow studies because the number of flows is few and their structural attitudes were difficult to measure accurately. The other six results are rotated counterclockwise in azimuth by amounts ranging from 12 to 77°. Because the inclinations are so steep, relatively small errors in the paleomagnetic directions and North American reference poles can cause much larger errors in azimuthal rotations. Hence only three of the rotations are larger than the formal 95% confidence limits, which are themselves minimum estimates. These three rotations, however, do not exceed the confidence limits by a large margin (i.e., a factor of two). Systematic errors such as initial dip also would have large effects on the estimates of rotation. If such errors in structural correction were optimally oriented, dip errors from 10 to 20° would be required to account entirely for the three largest and most significantly counterclockwise rotations (nos. 5, 6, and 7, Table 2). Even greater errors would be necessary for nonoptimal orientations.

Even though the validity of any one rotation may be easily doubted, the probability of obtaining so many sizeable counterclockwise rotations over such a large region by coincidence alone is small. Furthermore, it is unlikely that the individual rotations are the entirely fortuitous result of independent rotations of small blocks, especially since the dextral slip that characterizes the major fault systems in Alaska would be expected to favor rotations of the opposite sense from that which is observed. For these reasons, we take the average of the results of various studies to get an estimate for possible regional rotation. The mean and standard error for the four studies of lava flows with ages between 60 and 68 Ma (nos. 2, 3, 6, and 7, Table 2) is $-30 \pm 13^\circ$. Each study was weighted equally, despite the obvious differences in quality, in order to take maximum account of possible regional variations in rotation. This may have led to an underestimation of the average rotation, however, because the relatively uncertain Nowitna Volcanics result (no. 3) with its 5° clockwise rotation is given too much influence. Taking only lava flow results that are each formally significant at greater than 95% confidence (nos. 6 and 7), the mean rotation is $-48 \pm 7^\circ$. If all seven results, with ages from 44 to 70 Ma, are averaged indiscriminately, a value of $-35 \pm 10^\circ$ is obtained.

Thus, it appears probable that a large portion of central and southwestern Alaska has undergone counterclockwise rotation of about 30 to 50° during latest Cretaceous and Early Tertiary time. Various hypotheses involving rotation of large portions of Alaska have been suggested previously by several authors. Carey (1955) applied his orocline hypothesis to Alaska, postulating a 28° counterclockwise rotation of most of Alaska about a pivot
point north of the Gulf of Alaska in the Alaska Range at an unspecified time after the Triassic period. Carey called upon this rotation to open the Arctic Basin "sphenochasm" and bend the mountain ranges of Alaska into their present configuration. Subsequent rotation models can be divided into two categories. (1) Northern Alaska undergoes Late Jurassic to mid-Cretaceous counterclockwise rotation of approximately 70° about a more northerly pivot point, thereby opening the Canada Basin and causing the Brooks Range thrusting (Rickwood, 1970; Tailleur, 1973; Sweeney et al, 1978; Mayfield et al, 1983). Early paleomagnetic results (Newman et al, 1979) appeared to support this model, but subsequent analysis showed these data to be inapplicable because the rocks were remagnetized (Hillhouse and Grommé, 1983b). A pervasive Cretaceous thermal event is thought to be the cause and appears thus far to have thwarted further paleomagnetic efforts in northern Alaska to test the hypothesis of counterclockwise rotation. (2) Central and southern Alaska rotate 40 to 55° counterclockwise during latest Cretaceous to Early Tertiary time, not as one block but as several narrower blocks separated by faults, very much like a huge chevron fold or kink band (Grantz, 1966). Simultaneously, northwestern Alaska and eastern Siberia buckle and shorten under east-west compression, and the part of Alaska in compression is largely decoupled by the Kaltag fault from the part lying to the south (Patton and Tailleur, 1977). The two categories of models are not mutually exclusive, because the rotations occur at different times and involve different parts of Alaska. In both, Eurasia–North America convergence is regarded as the motive force.

The paleomagnetic data under discussion here are clearly pertinent to the second type of model in which Late Cretaceous to Early Tertiary rotation is expected. The paleomagnetically inferred rotations are consistent in both sense and magnitude with those that Grantz (1966) predicted by restoring right-laterally offset Late Cretaceous features on the Kaltag, Iditarod, and Farewell faults (Fig. 2). Grantz also pointed out that these same rotations very nearly straighten out the great bends in the Denali–Farewell and Tintina–Kaltag fault systems. Recent plate-motion models based on marine magnetic anomalies in the North Atlantic (Engebretson, 1982) indicate that the period of convergence between North America and Eurasia was between about 95 and 53 Ma. The amount of convergence implied by Engebretson's (1982) stage poles and angular rotations is sufficient to have rotated Alaska south of the Kaltag fault by a maximum of 68° (less than that if Siberia underwent complementary clockwise rotation during collision). Using (1) the finite difference poles originally found by Srivastava (1978) from his analysis of magnetic anomalies associated with the opening of the North Atlantic, and (2) the anomaly time scale of Harland et al (1982), we calculate that 63% of the total convergence occurred between 67 and 53 Ma. This corresponds to counterclockwise rotation of 43°. The paleomagnetic results in Table 2 that are the most reliable and statistically significant (nos. 6 and 7; both from lava flows, and with mean azimuthal rotation approximately twice the 95% confidence limit) indicate a mean counterclockwise rotation of 48° since 67 Ma, in good agreement with the predicted value.

The counterclockwise rotation of the 52 Ma lava flows in the Talkeetna Mountains (no. 1) postdates this period of convergence between Eurasia and North America. This rotation (−38 ± 46°), although not significant at 95% confidence, may still be real; if so, it clearly requires a different explanation if the analysis and dating of the marine magnetic anomalies are accurate. Assuming locally rigid plates, Stout and Chase (1980) have made a detailed analysis of the sharply curved segment of the Denali fault system 70 km (43 mi) northwest of the Talkeetna locality. They concluded that displacement around the bend has occurred in Early Tertiary time and that this would entail significant counterclockwise rotation. To explain the rotations observed in Bristol Bay by this mechanism, however, would require that region to also have been displaced around the bend. This would necessitate about 900 km (559 mi) of dextral displacement on the Denali fault since 68 Ma, which is more than twice the maximum estimate that has been proposed (Lanphere, 1978).

Southern Terranes

The 25 ± 7° mean northward displacement of the Prince William terrane inferred from the lava flows of the lower Paleocene Ghost Rocks Formation is the most comprehensive and probably the most reliable paleomagnetic result from the southern terranes (nos. 20 and 21). Nonetheless, it is not unimpeachable, especially in isolation. Fortunately, it is reinforced by the 24 ± 12° displacement determined for slightly older pillow lava and dikes (no. 19) of the Chugach terrane. Although the contact between the Chugach and Prince William terranes is a fault with evidence for right-lateral slip (J. Sample, 1984, personal communication), there is some reason to believe that the offset has not been great in paleomagnetic terms (Moore et al, 1983; Davies and Moore, 1984). As discussed above, the paleomagnetic determinations from sediments in these terranes are equivocal. Thus, there is a critical need for additional careful studies of paleomagnetically suitable material to test the reliability of these two results.

There are no results of comparable age from the Peninsular terrane or Wrangellia that we think are reliable. Insignificant, or even slightly southward displacement, however, is inferred from lava flows of early Eocene age (no. 1, Table 2) that lap from the Jura–Cretaceous flysch basin onto the northernmost part of Wrangellia. In addition, we have nearly completed studies of more than 50 lava flows with dates between 30 and 40 Ma at seven localities on the Peninsular terrane that are spread between the Lake Clark and Bruin Bay faults in the Lake Iliamna area (Thrupp and Coe, 1984). Taken together, these have a 95% confidence limit of around 5° and indicate no significant latitudinal movement since eruption. These two results are not compatible with the hypothesis of northward displacement at an average rate of 6 cm/year (2.4 in./year) throughout the Tertiary (Stone et al, 1982). The possibility remains, however, that more outboard portions of the Peninsular terrane could have somewhat greater northward displacements and thus have continued significant motion until later.

Eight of nine results in Table 2 and Figure 2 show counterclockwise azimuthal rotation of Prince William–Chugach terrane rocks. The one that does not (no. 20)
appears to have been affected by structural complications not typical of most of the Ghost Rocks Formation. In addition, we made the case earlier that nos. 22 and 26 may well have been overprinted, and so we shall not consider them further. This still leaves six studies rotated counterclockwise at three widely separated places: the Shumagin Islands, Kodiak Island, and the Gulf of Alaska. As discussed earlier, the declinations from sediments might be reliable even when the inclinations are not. The mean counterclockwise rotation since about 70 Ma for the three places is 53 ± 23°, comparable with the paleomagnetically inferred counterclockwise rotation of the inboard portion of Alaska previously discussed. Rotation of the displaced southern Alaska terranes may have been caused by a combination of orocinal bending and by jamming around a preexisting bend in the margin. Moreover, there appears to be a large decrease in amount of rotation from east to west in the Prince William–Chugach terranes. If this is a real trend and not just a coincidence, it would suggest the hypothesis of substantial indentation and shortening concentrated in the Gulf of Alaska area that has been proposed by Moore et al. (1983). Such a process (Perez and Jacob, 1980; Plafker, 1983; von Huene et al. this volume) is apparently occurring today with the ongoing collision of the Yakutat block (YA on Fig. 2).

The azimuthal rotations indicated by the studies on the Peninsular terrane are inconsistent in both sense and magnitude. Although there might be a sensible pattern in time and space that will become apparent with the addition of more data, our impression at this time is that the variation is quite capricious. This may reflect the competing effects of different mechanisms of rotation: regional counterclockwise rotation caused by the same mechanisms as discussed above for the Prince William and Chugach terranes with superimposed local clockwise rotations of blocks in response to dextral displacement along strike-slip faults.

**PROPOSED SCENARIO**

The ultimate goal is to integrate the paleomagnetic, plate tectonic, and geologic data into a single coherent story. This would be a formidable task even without the large gaps and inconsistencies that are present in the data. What we will attempt to do instead is outline some of the more likely possibilities for the kinematic history, discuss some of the issues, and point out various problems.

The terranes north of the Peninsular terrane appear to have been, from the standpoint of the broad-brush characterization of paleomagnetism, essentially in place by latest Cretaceous time. The same paleomagnetic data suggest, however, that much of western and central Alaska rotated counterclockwise approximately 40° since latest Cretaceous, probably in a manner first described by Grantz (1966). A major cause of such an event could have been North America–Eurasia convergence between 67 and 53 Ma, the direction and magnitude of which appears able to account for much of the rotation.

For a variety of reasons mentioned previously, accretion of the Wrangellia–Peninsular composite terrane to North America probably occurred no later than the Late Cretaceous. Analysis of plate motions suggests it moved northeastward on the Kula plate until it collided with North America (Engelbreton, 1982). The question is, Where did this initial collision occur? Although there are no paleomagnetic displacement data that we believe are quantitatively dependable, the Late Cretaceous and early Paleocene studies certainly convey the impression that these terranes lay to the south relative to cratonic North America (Fig. 2), as does the occurrence of pieces of Wrangellia along the North American margin. Moreover, paleomagnetic data from Cretaceous intrusive rocks in the Stikinia terrane and the Coast Plutonic Complex, both in the Canadian Cordillera, suggest 10 to 20° of northward displacement of inboard terranes (Irving et al., 1980, 1983), probably along the Tintina fault system, since mid- to Late Cretaceous time. According to Irving (1984, personal communication), the upper limit of 20° northward displacement of the Coast Plutonic Complex is presently favored, although that figure is subject to the uncertain error of ambiguous tilt inherent in intrusive rocks.

 Geological evidence has been cited as well for 1,400 km (870 mi) of cumulative dextral slip: 1,000 km (621 mi) along the Tintina fault system sometime after mid-Cretaceous and before late Eocene time (Gabriele, in press), and 400 km (249 mi) of displacement, probably post-early Tertiary, on the Denali fault (Lanphere, 1978; Nokleberg et al., in press). Since geological determinations of slip on faults tend to be minimum estimates of terrane displacements, the paleomagnetic estimate of 20° northward displacement is not unreasonable.

This would place the collision of the Alaskan part of Wrangellia at a present-day latitude of 40° relative to North America (just north of Cape Mendocino). Displacement of Wrangellia, the Peninsular terrane, and at least part of the Jura–Cretaceous flysch belt northward along the continental margin was probably driven by the oblique subduction of the Kula and perhaps the Izanagi plates (Engelbreton, 1982). The important paleomagnetic result of Hillhouse and Grommé (1983a) from the Talkeetna Mountains places the arrival of at least the northern part of the Wrangellia–Peninsular composite terrane to interior Alaska earlier than about 52 Ma.

A problem arises with this and any other scenario that involves large terrane displacements on the Tintina or Denali faults. How was this displacement accommodated in interior Alaska? Only about 130 km (81 mi) of right-lateral offset is inferred for the Kaltag fault from Late Cretaceous to present (Patton and Tailleur, 1977), so that large Tintina offsets during that time would have had to be accommodated elsewhere. Perhaps the dextral motion used to continue northwestward along other faults such as the Kobuk on the south side of the Brooks Range, a possibility mentioned by Grantz in 1966. Yet another possibility is that Tintina motion was redistributed on a series of faults, both known and unknown.

Relative to North America, the mean paleomagnetic inclination found for the Ghost Rocks volcanics would put the Prince William terrane of Kodiak Island 25 ± 7° further south in early Paleocene time. This result is reasonably consistent with the 20° of post-mid-Cretaceous displacement found for the Coast Plutonic Complex. Since
the Coast Plutonic Complex is linked to the Vancouver Island segment of Wrangellia by Late Cretaceous time (Monger et al, 1982) and is separated from the Alaskan segment of Wrangellia by the Denali fault system, its displacement is presumably somewhat less than that of the Wrangellia and Peninsular terranes as well. Moore et al (1983) discussed the geological constraints for Kodiak Island and concluded that most likely Kodiak collided with the margin of proto-Alaska in the Eocene. One reason is that the expected uplift would account nicely for the formation of the Zodiac fan just to the south of Kodiak in Eocene-Oligocene time. Paleontological evidence from Middleton Island also suggests that Kodiak Island was at least as far north as 50° ± 5° paleolatitude by 42 Ma (Keller et al, 1984; von Huene et al, this volume). This is consistent with existing plate models. Assuming translation beginning at 62 Ma along a simplified, restored North American continental margin at a rate equal to the component of Kula plate velocity resolved parallel to that margin, a paleolatitude of 55° is reached by 42 Ma (Engebretson, 1982, and personal communication). There would still remain 30% of the total latitudinal displacement relative to North America to be accommodated. This residual motion would have to be driven by the slower moving Pacific plate, with attendant shortening of proto-Alaska, and continue until about 10 Ma to emplace Kodiak in its final position. However, the uncertainty of the paleomagnetically inferred displacement permits considerable range in the details of such kinematic modeling.

In general terms, the scenario described above appears quite consistent and reasonable for the most outboard, Prince William terrane. Problems emerge if one applies ties suggested by the presence of distinctive 60 Ma intrusive rocks in the Prince William, Chugach, and Peninsular terranes (Moore et al, 1983; Davies and Moore, 1984). These plutons occur in a long belt within the Prince William and Chugach terranes, but only one location is known thus far in the Peninsular terrane, just northwest of the Border Ranges fault on Kodiak Island (Davies and Moore, 1984). If these intrusive ties were tight, the Peninsular terrane and presumably Wrangellia would have had to move with the Prince William terrane and consequently would not have arrived at proto-Alaska by 52 Ma. In fact, they would only have completed about two-thirds of their total inferred displacement by then. However, arrival of the Wrangellia-Peninsular composite terrane by this time is required by the concordant paleolatitude determined from 52 Ma lavas of the Talkeetna Mountains, which overlie parts of Wrangellia and the flysch basin to the north.

It may be more realistic to regard these intrusive ties as loose, that is, to allow for the possibility of hundreds of kilometers of intertongue displacement while still maintaining juxtaposition of distinctive suites of igneous rocks. For example, it is possible to accommodate up to 500 km (311 mi) of slip on the contact fault between the Prince William and Chugach terranes and about 600 km (373 mi) of slip on the Border Ranges fault between the Chugach and Peninsular terranes, without completely offsetting the Gulf of Alaska magmatic belt. In addition, there are numerous intraterrane faults that could quite conceivably have accommodated significant transient motion not attributable to intertongue displacements. Some possible examples are the Uganik thrust within the Chugach terrane and the Bruin Bay and Castle Mountain–Lake Clark faults within the Peninsular terrane (Fig. 2).

Further evidence in support of the notion of substantial dextral slivering within the southern terranes is provided by similarities in the geologic histories of the Leech River Complex of southern Vancouver Island and schists on Baranof Island, which were recognized by Cowan (1982). The interpretation that he favors involves a minimum of 1,000 km (621 mi) of dextral slip between the Chugach terrane and the Peninsular-Wrangellia composite terrane and requires that this major displacement occurred entirely after 40 Ma.

In view of this interpretation and other arguments presented above, there is scope for considerable relative displacement between the Peninsular-Wrangellia terranes on the one hand and the Prince William and Chugach terranes on the other. Thus, both the geologic evidence and the paleomagnetic constraints can be incorporated into a reasonably consistent kinematic history involving coastwise displacement along a series of strike-slip faults. In this scenario Wrangellia and the Peninsular terrane move approximately 20° northward relative to cratonic North America between mid-Cretaceous time and 52 Ma, while the Prince William and Chugach terranes travel about 25° northward throughout Paleogene and perhaps even during Neogene time.

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APPENDIX A

Analyses of geomagnetic and paleomagnetic field data (Cox, 1970; Harrison, 1980) have shown repeatedly that the distribution of directions recorded at a site over a period of time is significantly less Fisherian than that of the corresponding virtual geomagnetic poles (VGP—Cox and
Doell, 1960). Thus, when using Fisher (1953) statistics to analyze paleomagnetic data, it is preferable to work with poles rather than directions. Sample directions are averaged to find the mean direction for a site, which is then transformed to the corresponding VGP using a standard algorithm (e.g., McClellinny, 1973, p. 25). Next, the N site-mean VGPs are averaged to yield the mean paleomagnetic pole and the associated 95% confidence limit $A_{95}$ and precision parameter $K$ are found using Fisher's formulas (e.g., McClellinny, 1973, p. 79).

Given the latitude and longitude of the sampling area $(\lambda_0, \phi_0)$ and of the experimentally determined paleomagnetic pole $(\lambda_p, \phi_p)$, the observed paleolatitude $\lambda_0$ can be found using

$$\text{PLAT} = \lambda_0 = \sin^{-1} [\sin \lambda_0 \sin \lambda_p + \cos \lambda_0 \cos \lambda_p \cos (\phi_p - \phi_0)]$$  \hspace{1cm} (A1)

The uncertainty in the observed paleolatitude (95% confidence limit) is

$$\lambda_0 = C A_{95}$$  \hspace{1cm} (A2)

where $C$ can be calculated by methods given by Demarest (1983). We have used $C = 0.78$ consistently, though the actual value varies considerably when inclinations are steep and $A_{95}$ is large.

Often, however, only the mean paleomagnetic direction and associated confidence limit $A_{95}$ and precision parameter $k$ are presented in the literature. Unless the individual site-mean directions are available, the analysis cannot be redescribed in terms of poles because the individual VGPs are not known. However, a reasonable estimate can be computed for the precision parameter of the distribution of poles from the precision parameter given for the distribution of directions and the paleolatitude $\lambda_0$ (Cox, 1970):

$$K = k (5 + 3 \sin^2 \lambda_0) / [2 (1 + 3 \sin^2 \lambda_0)]$$  \hspace{1cm} (A3)

where paleolatitude is now found from the inclination $I$ using the dipole formula

$$\lambda_0 = \tan^{-1} (0.5 \tan I)$$  \hspace{1cm} (A4)

The confidence limit $A_{95}$ for the distribution of poles is then obtained from the relations of Fisher (1953) statistics:

$$A_{95} = \cos^{-1} [1 - (N-R)(20^{1/(N-1)}-1)/R]$$  \hspace{1cm} (A5)

$$R = N - (N-1)/K$$  \hspace{1cm} (A6)

where $N$ is the number of samples.

To find the latitudinal displacement with respect to the North American craton, the expected paleolatitude $\lambda$, must be found by substituting the latitude and longitude of the appropriate North American reference pole (Table 4) for $\lambda_p$ and $\phi_p$ in (A1). Then the latitudinal displacement is

$$\text{DISPL} = d = \lambda_r - \lambda_0$$  \hspace{1cm} (A7)

and the 95% confidence limit on the latitudinal displacement follows from (A2):

$$\Delta d = (\Delta \lambda_0^2 + \Delta \lambda_r^2)^{1/2}$$  \hspace{1cm} (A8)

To find the azimuthal rotation with respect to cratonic North America, the angle between the great circle passing through the site and the mean observed pole and the great circle passing through the site and the mean expected pole must be found. The azimuth of the former great circle is just the mean observed declination $D_0$ corresponding to the mean observed pole. It can be calculated by reversing the standard algorithm relating paleomagnetic direction at a site to its corresponding pole (e.g., McClellinny, 1973, p. 25). Likewise, the azimuth of the latter great circle is just the expected declination $D_r$ corresponding to the reference pole, which can be calculated from the same algorithm.

The azimuthal rotation is therefore

$$\text{ROT} = r = D_0 - D_r$$  \hspace{1cm} (A9)

The 95% confidence limit on ROT is

$$\Delta r = (\Delta D_0^2 + \Delta D_r^2)^{1/2}$$  \hspace{1cm} (A10)

where the individual confidence limit on $D_0$ or $D_r$ is given by

$$\Delta D = C \sin^{-1} (\sin A_{95} / \cos \lambda)$$  \hspace{1cm} (A11)

**REFERENCES**


Table 4

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Ref: A. Irving and Irving, 1982; B. Diehl et al., 1983.

N: Number of paleomagnetic sites or (*) studies (each with many sites).
Δ: Angular discrepancy between poles from references A and B.

Table 4—Paleomagnetic reference poles used for North American Craton.


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