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Chapter 26

Paleomagnetic data from Alaska

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INTRODUCTION

During the past decade, the study of paleomagnetism has provided compelling evidence for the displacement and accretion of Alaskan terranes. As indicated by paleomagnetic measurements of ancient latitudes, large areas of crust that now form part of Alaska were once located at lower latitudes with respect to the North American craton. Triassic volcanic rocks, for example, in the Wrangellia terrane of southern Alaska show a poleward shift in latitude greater than 27° (3,000 km). The large displacements that we infer from paleomagnetic data are consistent with the concept that most of Alaska is made up of displaced lithotectonic terranes, which Silberling and others (this volume) defined on the basis of paleontologic and stratigraphic differences. Paleomagnetic studies provide the basic data for measuring the rates of movement and for determining the arrival times of far-travelled terranes along the continental margin. Using this information, we can refine plate-tectonic models by comparing terrane movements with predicted relative motions between North America and the oceanic plates of the Pacific basin.

Paleomagnetic poles from the stable part of North America define a frame of reference for comparison with the paleolatitudes of Cordilleran terranes. This frame of reference, sometimes called the apparent polar wander (APW) path, has been compiled from numerous studies undertaken during the past three decades (McElhinny, 1973, p. 201–206; Irving, 1979; Irving and Irving, 1982). By 1970, the confirmation of sea-floor spreading and the refinement of cratonic reference poles strengthened the interpretation that paleomagnetic anomalies in the Cordillera were the result of translations and rotations of large-scale crustal blocks. In one of the early studies of paleomagnetism in British Columbia, Irving and Yole (1972) presented evidence for the northward movement of Vancouver Island, and proposed that the island is a remnant of a now-subducted oceanic plate. At about the same time, Packer and Stone (1972) presented paleomagnetic evidence for the northward movement of southern Alaska, and suggested that it was a continental fragment from the southwestern margin of North America. Since 1975, the pace of paleomagnetic research in Alaska has accelerated, and we are developing a clearer picture of the accretionary history of the region.

In this chapter, we review paleomagnetic evidence regarding accretionary tectonics in Alaska, paying particular attention to quality of the data according to reliability criteria, such as the fold test. We summarize the major tectonic events that are inferred from the paleomagnetic data, and then propose a plate-tectonic model for Alaska by integrating the displacement histories of terranes and of oceanic plates within the Pacific basin.

PALEOMAGNETIC METHODS

The central assumption of paleomagnetic methodology is that the geomagnetic field, when averaged over a sufficient interval of time, has a geocentric dipole source that is aligned with the Earth's rotational axis. When these conditions are met at a given site, the mean geomagnetic latitude equals the geographic latitude. Geomagnetic secular variation, which is caused by wobble of the dipole axis and by changes in the non-dipole component of the field, is roughly symmetrical about the rotational axis when sampled over a time interval of several thousand years. Sufficient time averaging of the geomagnetic signal is therefore an important requirement of the geocentric axial dipole (GAD) assumption and of paleolatitude determinations. The GAD assumption has been shown to be true to within a few degrees by worldwide compilations of paleomagnetic data from volcanic rocks younger than 5 Ma (McElhinny and Merrill, 1975). The assumption of a dipole field also holds for high-latitude sites in Alaska, as shown by a study of young basalts on Nunivak and the Pribilof Islands (Cox and Gordon, 1984).

As summarized by Merrill and McElhinny (1983), much research has been directed toward testing the validity of the GAD assumption for times prior to 5 m.y. ago. Late Mesozoic continental reconstructions of Pangea, which are independent of paleomagnetic pole determinations, confirm that the geomagnetic field had a geocentric dipole source since Jurassic time. This fact is demonstrated by the general agreement of continental APW paths when spreading in the Atlantic and Indian Oceans is backtracked according to the pattern of magnetic stripes on the sea

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floor. However, proving that the dipole source has always been aligned with the rotation axis requires independent evidence of ancient latitude, such as the distribution of coral, limestone, and other paleoenvironmental indicators. In studies of Proterozoic and younger rocks, these indicators generally form a more consistent pattern when plotted in terms of paleomagnetically derived latitudes as opposed to their present positions. This observation supports the GAD assumption, but lacks the resolution to prove the assumption conclusively.

Another approach to the GAD question uses oceanic hot spots (the Hawaiian Islands, for example) and the corresponding seamount chains to establish an absolute frame of reference for the lithosphere (Morgan, 1972; Duncan, 1981). Under the assumption that the hot spots have remained fixed relative to each other, the relative position of the rotation axis can be determined for each plate for periods back to about 150 m.y. ago. Then, for each plate, a comparison can be made between the position of the "hot spot" rotational pole and the time-averaged paleomagnetic pole (Jurdy, 1981; Harrison and Lindh, 1982; Gordon, 1983; Andrews, 1985). This comparison shows that the paleomagnetic pole has deviated as much as 20° from the "hot spot" reference pole during the Early Jurassic; the deviation decreased sharply during the early Tertiary. Any long-term separation of the two poles could be explained either by a shift of the entire lithosphere relative to the rotational axis (true polar wander), which would not necessarily violate the GAD assumption, or by prolonged wandering of the magnetic dipole axis away from the rotational axis. True polar wander can occur as a consequence of changes in the principal moment of inertia of the rotating, viscous mass of the Earth (Goldreich and Toomre, 1969). Long-term wandering of the dipole is less likely, given the positive paleoclimatic evidence and the known stability of the GAD field during the last 5 m.y.

The basic quantity that is measured in the paleomagnetic laboratory is the magnetic field direction of a rock, a vector specified by its inclination (plunge from horizontal) and declination (azimuth from true north). Given the assumption of a GAD field, the inclination (I) determines the paleolatitude (L) by the simple dipole formula: $2 \tan L = \tan I$. For bedded rocks, the magnetic inclination is easily determined relative to the ancient horizontal, so tilt of the rocks poses no problem in paleolatitude calculations. Magnetic field vectors are corrected for tilt of the beds by simply rotating the vector about the strike by the angle of dip. Tectonic rotations about a vertical axis are inferred from the paleomagnetic declination, when it is compared to the appropriate reference value. The simple tilt correction sometimes introduces errors in declination, especially in complexly deformed regions where there may be localized rotations about the vertical axis, oblique slip on faults, or multiple episodes of folding. Paleolatitudes, which are not affected by local structures, are therefore emphasized in the analysis of terrane movements.

The paleomagnetic pole is calculated from the mean paleomagnetic direction by use of the axial dipole formula. The inclination sets the angular distance (P) from the sampling site to the pole by the equation: $\cot P = \frac{1}{2} \tan I$, and the declination is the azimuth to the pole. Poles are particularly useful for combining paleomagnetic data from a large region, because the calculation corrects for the dipole field variation between distant sites. At a given site, the angular distance to the paleomagnetic pole of the site can be compared directly with the distance to the appropriate cratonic reference pole; a difference means that the site has moved in latitude relative to the craton. For simplicity a displacement to higher latitudes is termed "northward drift," although "poleward drift" is more correct because "north" changes as the craton moves.

Paleolatitudes are specified uniquely, whereas paleolongitudes are not. Consequently, the original position of a displaced terrane cannot be specified exactly by a single paleomagnetic pole, and displacements in latitude are only the minimum displacement that may have taken place. Also, tectonic rotations are not uniquely specified by a paleomagnetic pole unless the axis of rotation is constrained by independent geologic evidence.

Measuring the remanent magnetism of rocks will yield a valid paleomagnetic pole and paleolatitude if the following criteria are met: (1) the magnetization was acquired during or soon after deposition, (2) a sufficient number of samples were collected to establish a statistically valid magnetic direction, and (3) the collection represents thousands of years of geomagnetic secular variation to yield a geocentric axial dipole direction. Hence, the sampling scheme must be designed to meet these time and statistical constraints before the data can chart reliably the movements of terranes.

Metamorphism, chemical alteration, acquisition of viscous remanent magnetization, and lightning are the main sources of secondary magnetizations that mask the original magnetic signals in rocks. Practically all specimens, especially those from orogenic belts, must be treated in the laboratory to strip away magnetic overprints to reveal the underlying primary component. The common demagnetization techniques employ alternating fields (AF) or heating followed by cooling in a field-free furnace (thermal demagnetization). The change in magnetic direction during such treatments is analyzed either graphically on an orthogonal vector diagram (Zijderveld, 1967) or computationally by line-fitting methods (Kirschvink, 1980). These methods of magnetic vector analysis reveal the components that make up the total magnetization and ensure that a stable magnetic direction has been isolated in each rock specimen.

Once the stable component is identified, several tests help to ascertain whether or not the magnetization was acquired at the time of deposition. The fold test establishes the necessary condition that the magnetization pre-dates any folding of the strata. In applying the fold test, a comparison is made of the angular dispersion of magnetic directions before and after corrections are made for the tilt of the bedding, preferably from the opposite limbs of a single fold. The test is positive when application of the bedding corrections significantly decreases the angular dispersion of directions. Another useful test is termed the "consistency of reversals," which compares the mean directions of normal and reversed polarity specimens. If the two means are 180° apart, at least within the confidence limits of the means, the test is positive. A positive result reduces the probability that the data contain a secondary component that might have survived the demagnetization treatments. The "conglomerate test" can be applied when cobbles of the sampled strata occur in an overlying conglomerate bed. If the lower bed gives a coherent magnetic direction while the cobbles give a random distribution of directions, then the possibility of complete remagnetization of the strata can be ruled out. None of these tests prove that the age of magnetization equals the age of the rock; however, when all possible tests are positive, they virtually eliminate the possibility of an undetected secondary component due to heating or alteration.

Paleomagnetic vectors, given either as field directions or as poles, are usually assigned a confidence limit, the α_{95}, which encircles the mean vector. In practical terms this statistic means that the true mean of all vectors in the population will lie within the confidence circle of the sample population with a 95 percent probability. Because the α_{95} is a type of standard error, its radius decreases as the number of specimens increases; enough samples therefore must be collected to obtain a reasonably small confidence limit. The number of samples must also meet the criterion that the collection represents enough time to average out geomagnetic secular variation and thereby yields a geocentric axial dipole direction. Studies of the recent geomagnetic field indicate 2,000 to 10,000 yr as reasonable intervals for obtaining the dipole direction. Estimating the time span of a particular collection is very difficult, although inferences can be drawn from biostratigraphy, the presence of paleosols, the occurrence of magnetic reversals (a polarity transition requires about 1,000 yr), or isotopic dating. As a rough rule of thumb, 15 sites distributed over a reasonable stratigraphic interval is the minimum number to satisfy the statistical and time-representative requirements of a reliable paleomagnetic pole. The vector from each site should be averaged from 2 or more independently oriented specimens. Ideally, the sites should be distributed over a sizable geographic area that provides opportunity for a fold test.

PALEOMAGNETISM OF ALASKAN TERRANES

The following discussion of paleomagnetic results from the Alaskan terranes is keyed to Figure 1, which shows the distribution of paleomagnetic studies in pre–Late Cretaceous rocks, and to Figure 2, which shows results from Late Cretaceous and younger rocks. Hillhouse (1987) published tables of data that are depicted in Figure 1. Our discussion emphasizes the reliability of the results, as interpreted from the quality tests described above. Unless otherwise noted, locations of geologic, physiographic, and tectonostratigraphic features referred to in this chapter are respectively shown on Plates 1 (Beikman), 2 (Wahrhaftig), and 3 (Silberling and others) in this volume (also see Plafker and Berg, this volume, Chapter 33).

The Peninsular and Wrangellia terranes

Packer and Stone (1972, 1974) published the first paleomagnetic evidence that parts of Alaska have moved to higher latitudes relative to the North American craton. The original intent of their study was to use paleomagnetic poles from Jurassic rocks of the Alaska Peninsula to test for oroclinal bending of Alaska, as postulated by Carey (1955) and others. Packer and Stone collected their samples from Jurassic sedimentary rocks of the Naknek Formation, the Tuxedni Group, the Chinitna Formation, and from Jurassic quartz diorites on the western limb of the orocline (Burk, 1965). The surprising result was a paleolatitude for the Alaska Peninsula that was 19° lower than would be predicted for the region from the North American APW curve. Packer and Stone concluded that southern Alaska had drifted northward from an original position near the Oregon coast, and proposed a model similar to the present rifting and northward motion of Baja California. The "Baja Alaska" model was refined by the addition of Cretaceous and early Tertiary paleomagnetic results from the Alaska Peninsula (Stone and Packer, 1977, 1979). The Cretaceous poles fell into two groups, one defined by sites in the Upper Cretaceous Chignik Formation at Wide Bay and Chignik Lake, the other defined by sites in the Chignik at Herendeen Bay and the Shumagin Islands and in the Upper Cretaceous Hoodoo Formation at Canoe Bay. Paleolatitudes defined by these Cretaceous poles indicated that southern Alaska had moved approximately 25° south from its Jurassic position before beginning its rapid northward journey. Poles from the lower Tertiary Tolstoi Formation at Pavlof and Canoe Bays placed the Alaskan block near the latitude of Vancouver Island, requiring rapid northward drift of the block after 50 Ma.

These astonishing estimates of large-scale drift were attended by large uncertainties, not only in the error bars of the paleolatitude determinations but also in the overall reliability of the Peninsular terrane sedimentary rocks as clean recorders of the ancient geomagnetic field. For example, the generally mild deformation of the Naknek Formation precluded successful fold tests, because the angular dispersions of magnetic directions were not changed significantly by application of tilt corrections. All Jurassic results used in Packer and Stone's analysis were of one polarity, so they could not apply the test for secondary components that employs the antiparallelism of normal and reversed polarity magnetizations. They observed reversals in the Cretaceous and Tertiary rocks of the terrane, but the "consistency of reversals" test was not conclusive. Packer and Stone's experimental work did not demonstrate with certainty that the Mesozoic sedimentary rocks were free of secondary magnetic components, which might have been added to the primary remanence by heating during the extensive volcanism of the late Tertiary, or by chemical changes during weathering.

At about the same time as Packer and Stone's (1972) investigations, the concept that Alaska and British Columbia are composed of many far-travelled terranes was gaining acceptance following the stratigraphic studies of Monger and Ross (1971), Jones and others (1972), Monger and others (1972), and Berg and others (1972) (also see Nokleberg and others, this volume, Chapter 10). The recognition by Jones and others (1977) of Wrangellia as a large, displaced terrane was founded on its dis-

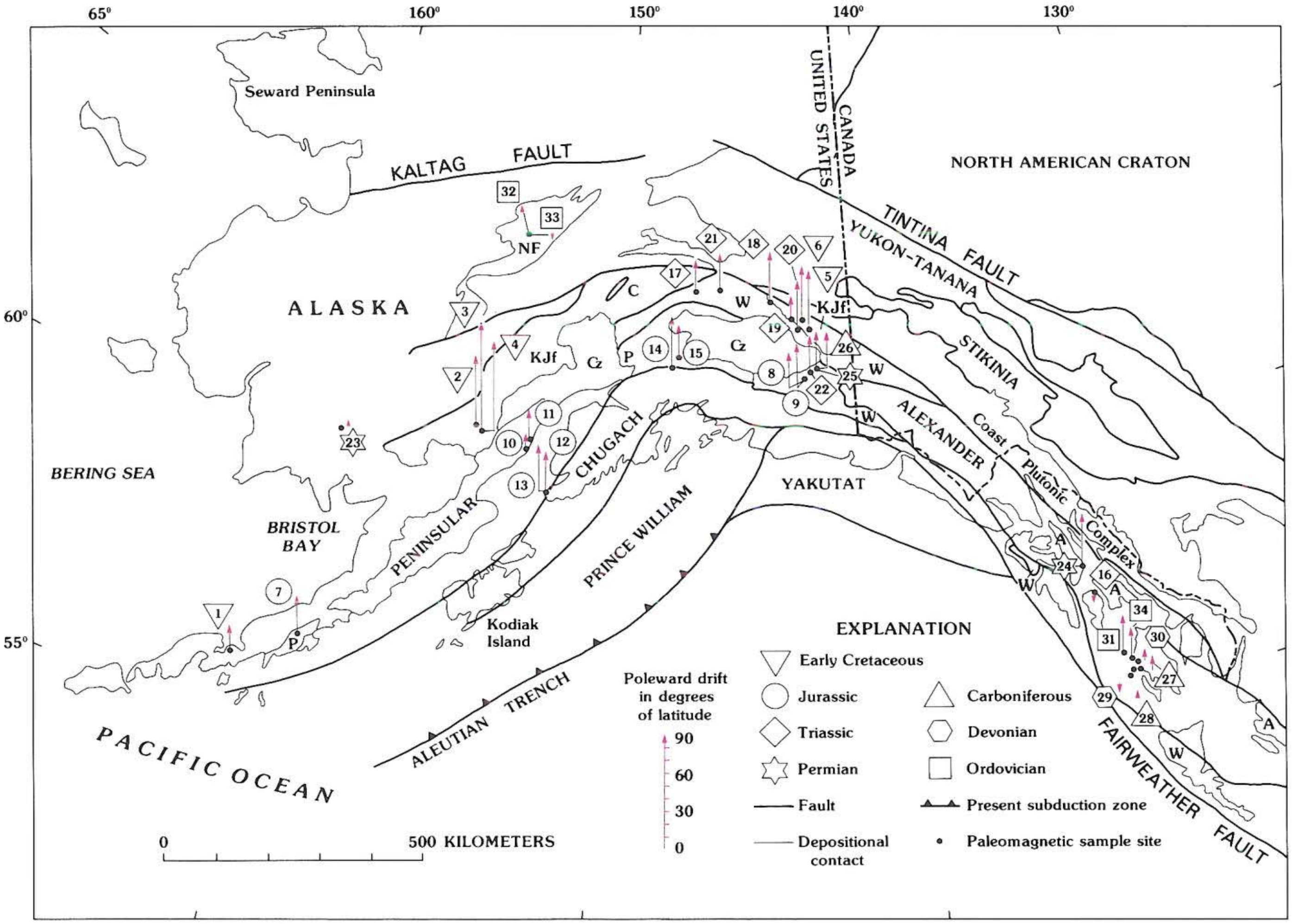

Figure 1. Latitudinal displacements inferred from paleomagnetic studies of pre–Late Cretaceous rocks in southern Alaska. Displacements are in degrees of latitude, assuming terranes originated in the northern hemisphere. Displacements to higher latitudes are indicated by upward arrows; downward arrows indicate displacements to lower latitudes relative to the North American craton. Terrane map modified from Jones and Silberling (1979) and Silberling and others (this volume). Selected terranes: A, Alexander; C, Chulitna; NF, Nixon Fork; P, Peninsular; W, Wrangellia. Sedimentary overlap assemblages: Cz, Cenozoic rocks, undifferentiated; KJf, Upper Jurassic and Lower Cretaceous flysch. See Table 1 of Hillhouse (1987) for references corresponding to the following paleomagnetic study areas: 1, Staniukovich Formation; 2–4, flysch near Lake Clark; 5, flysch near Nutzotin Mountain; 6, flysch near Nabesna; 7, Naknek Formation at Chignik Lake; 8–9, Nizina Mountain Formation; 10–11, Tuxedni Bay; 12–13, Talkeetna Formation at Seldovia Bay; 14–15, Talkeetna Formation in southern Talkeetna Mountains; 16, pillow basalt of Hound Island; 17, Nikolai Greenstone in Clearwater Mountains; 18, Nikolai Greenstone near Mentasta Pass; 19–20, Nikolai Greenstone near Nabesna; 21, Nikolai Greenstone in Mount Hayes Quadrangle; 22, Nikolai Greenstone near McCarthy; 23, basalt at Nuyukuk Lake; 24, Pybus Limestone; 25, Hasen Creek Formation; 26, Station Creek Formation; 27, Ladrones and Klawak Formations; 28, Peratrovich Formation; 29, Port Refugio Formation; 30, Wadleigh Formation; 31, lavas of the Descon Formation; 32, Telsitna Ridge; 33, Novi Mountain; 34, sedimentary rocks of the Descon Formation.

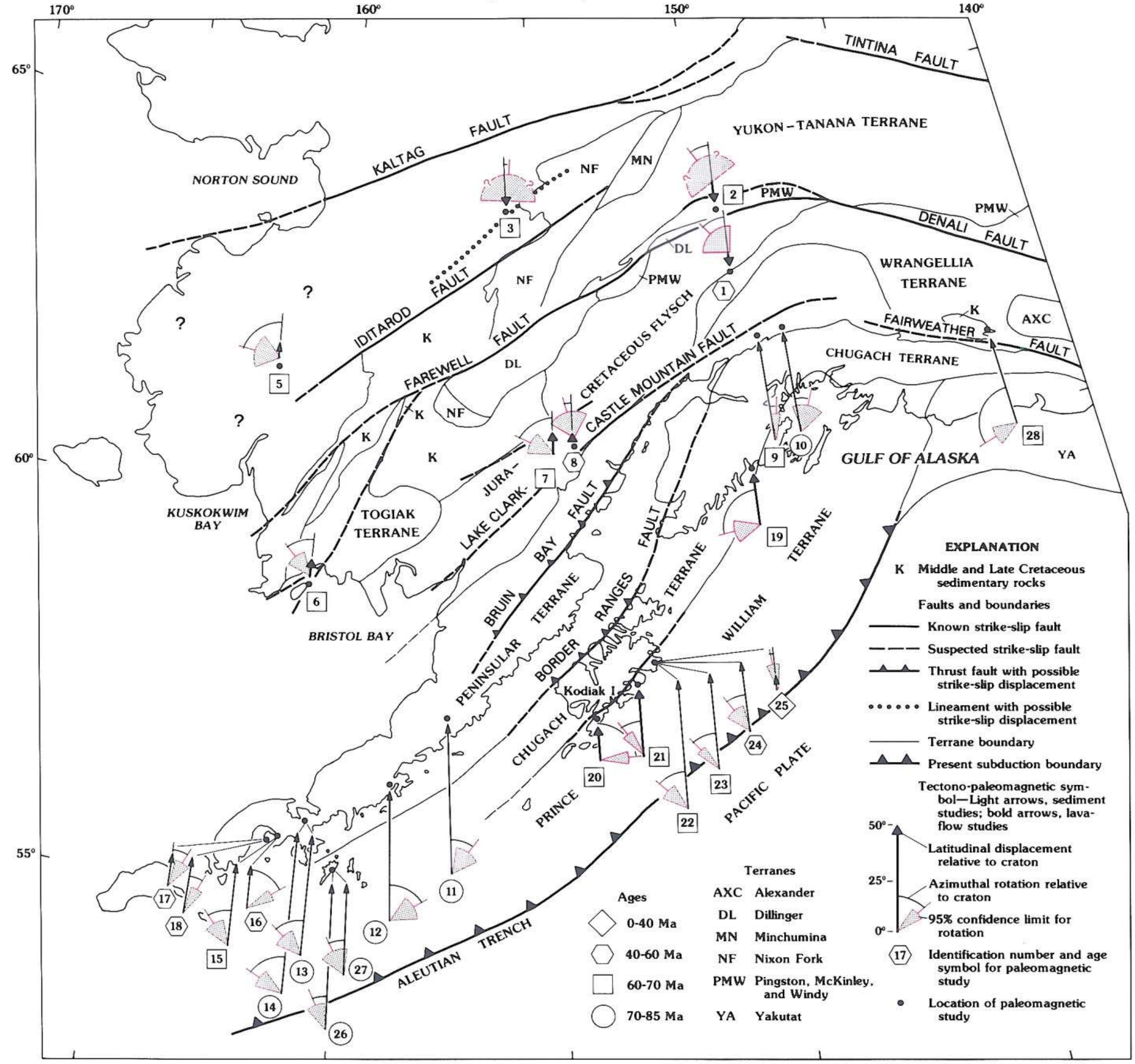

Figure 2. Latitudinal displacement and azimuthal rotation inferred from paleomagnetic studies of Late Cretaceous and younger rocks in Alaska, after Coe and others (1985). Bold arrows indicate results derived from volcanic rocks considered to be more reliable than sedimentary rocks for paleomagnetic study. See Table 2 of Coe and others (1985) for references. Sedimentary overlap assemblage: K, Cretaceous rocks. Identification numbers: 1, unnamed volcanic rocks, northern Talkeetna Mountains; 2, Cantwell Formation (lavas), Denali National Park; 3, Nowitna volcanic rocks, McGrath; 5, tuffaceous rocks, Ohogamiut Village; 6, unnamed volcanic rocks, northern Bristol Bay; 7–8, unnamed volcanic rocks, Lake Clark; 9, Chickaloon Formation, Matanuska Valley; 10, sedimentary rocks, Sheep Mountain; 11, Chignik Formation, Painter Creek; 12, Chignik Formation, Chignik Lagoon; 13–14, Chignik Formation, Herendeen Bay; 15, Hoodoo Formation, Canoe Bay; 16–17, Tolstoi Formation, Pavlof Bay; 18, Tolstoi Formation, Canoe Bay; 19, Valdez(?) Group, Resurrection Peninsula; 20, Ghost Rocks Formation (lavas), Alitak Bay, Kodiak Island; 21, Ghost Rocks Formation (lavas), Kiliuda Bay, Kodiak Island; 22, Kodiak Formation, Kodiak Island; 23, Ghost Rocks Formation (sedimentary rocks), Kodiak Island; 24, Sitkalidak Formation, Kodiak Island; 25, Narrow Cape Formation, Kodiak Island; 26–27, Shumagin Formation, Shumagin Islands; 28, MacColl Ridge Formation, McCarthy.

tinctive stratigraphy and its unique molluscan fauna compared to nearby terranes of similar age. Wrangellia contains a thick sequence of Triassic volcanic rocks that was the target of early paleomagnetic studies, providing clues to its exotic origin. In 1962, Richard R. Doell (U.S. Geological Survey) sampled the Triassic Nikolai Greenstone near McCarthy in the Wrangell Mountains; preliminary determinations gave magnetic directions that indicated anomalously low paleolatitudes, but this work was not pursued further for more than a decade. Before the terrane was recognized in British Columbia, Symons (1971) sampled the Triassic Karmutsen Formation on Vancouver Island and proposed northward displacement of the island as one of several possible explanations for the formation's unusual paleomagnetic pole. After careful thermal demagnetization experiments, Irving and Yole (1972) separated the Karmutsen magnetizations into a primary cooling component and an overprint, and postulated the northward displacement of Vancouver Island.

In 1976, the growing interest in the possible displacement of Wrangellia prompted more magnetic measurements of Doell's Nikolai collection (Hillhouse, 1977). The results were consistent with the low paleolatitudes that Canadian geologists had obtained from correlative volcanic rocks on Vancouver Island. At McCarthy, the paleolatitude derived from 50 lava flows was at least 27° south of the predicted Triassic latitude for the region, indicating that the terrane had moved 3,000 km north relative to continental North America. The magnetization of the Nikolai Greenstone was acquired before the rocks were folded, as indicated by a successful fold test, and the removal of secondary components was assured by the antiparallelism of normal and reversed directions. The magnetization had a high stability to thermal disturbances, as shown by thermal demagnetization experiments to 575°C.

Subsequent research on the Nikolai and its equivalents in Alaska, Oregon, and British Columbia confirmed the anomalously low paleolatitude of Wrangellia, adding credence to the concept of exotic terranes in the Cordillera (Yole and Irving, 1980; Schwarz and others, 1980; Stone, 1982; Hillhouse and others, 1982). In the Mt. Hayes Quadrangle of Alaska (Hillhouse and Grommé, 1984), some 250 km northwest of McCarthy, Triassic basalt of Wrangellia yielded a mean paleolatitude of 14°, similar to the latitude obtained at McCarthy (10°), on Vancouver Island (17°), and in Oregon (18°). All parts of Wrangellia apparently originated within 18° of the Triassic equator, after which fragments of the terrane were scattered along the continental margin from Oregon to Alaska. The fragment of Wrangellia in the Mount Hayes Quadrangle was carried the farthest north, at least $28° \pm 6°$ or approximately $3,100 \pm 660$ km.

If the polarity of the dipole field is not known, it is difficult to determine whether a paleomagnetically-derived latitude should be assigned north or south of the paleoequator. This ambiguity arises for far-traveled terranes, because the paleodeclinations are no longer diagnostic after the terranes have undergone large vertical-axis rotations. Such is the case for Wrangellia, where the Nikolai basalts were magnetized mainly in a field characterized by upward inclinations during a polarity interval of unknown sign. The options for interpretation are as follows: (1) if the dominant polarity mode is normal, then the terrane originated in the southern hemisphere; (2) if the polarity is reversed, the terrane originated in the northern hemisphere. The displacements described in the foregoing paragraph assume a northern hemisphere origin; if the southern hemisphere option is correct, the possible displacements would be increased by about 30°.

To resolve the ambiguous original position of Wrangellia, Panuska and Stone (1981) investigated the paleomagnetism of Pennsylvanian and Permian volcaniclastic rocks, which were deposited during the long reversed-polarity interval of the Permo-Carboniferous. Their preliminary data showed that magnetic directions of the Paleozoic volcaniclastic rocks are similar to those in the Triassic Nikolai Greenstone, leading them to favor the tropical zone of the northern hemisphere (15°) as the original position of Wrangellia.

Tracking the late Mesozoic displacements of Wrangellia and the Peninsular terrane hinges on the accuracy of Panuska and Stone's conclusion concerning the polarity of the Nikolai paleomagnetic results. In Middle Jurassic and younger Mesozoic time, Wrangellia and the Peninsular terrane were overlapped by a sequence of marine sedimentary rocks, including the Chinitna and Nizina Mountain Formations, whose paleomagnetic poles should be the same regardless of their substrate (Jones and Silberling, 1979). Panuska and Stone (1981) combined the paleomagnetic data from both terranes to define an APW curve for southern Alaska, and chose the polarity of the Peninsular terrane Jurassic rocks to minimize the separation between the Jurassic pole of the Peninsular terrane and the Triassic pole of Wrangellia. Stone and others (1982) used this curve to reevaluate the Peninsular terrane data, arguing that it and Wrangellia moved southward from the northern hemisphere during the Jurassic to a position near 30°S before the final northward movement occurred. We believe that other scenarios that satisfy the APW curve are possible, including one that keeps Wrangellia and the Peninsular terrane in the northern hemisphere throughout the Mesozoic, by allowing northern Wrangellia to rotate relative to the Alaska Peninsula.

Although the exact Mesozoic movements of Wrangellia and the Peninsular terrane remain open to speculation, the paleomagnetic data reveal an overall northward drift until the beginning of the Tertiary. Early Tertiary and Late Cretaceous volcanic rocks consistently yield high paleolatitudes, indicating that Wrangellia and the Peninsular terrane had ceased drifting north relative to the North American continent by 65 to 55 Ma (Fig. 2). Hillhouse and Grommé (1982a) and Hillhouse and others (1985) studied the paleomagnetism of early Tertiary volcanic rocks along a 75-km transect from Denali National Park to the Talkeetna River. The transect crosses northern Wrangellia, deformed Jurassic and Cretaceous flysch, several smaller terranes within the flysch, and the Denali fault. In Denali National Park, Paleocene volcanic rocks of the Cantwell Formation yielded a paleolatitude of $81 \pm 8°$, which is $9 \pm 8°$ higher than the latitude that would be predicted from cratonic poles. Panuska and Macicak (1986) combined those data with results of additional sampling of the Cantwell volcanic rocks, and determined a paleolatitude of 71 ± 10°. Their revision of the Cantwell paleolatitude brings it into close agreement with the reference paleolatitude for the region. Hillhouse and others (1985) obtained similar results from early Eocene andesites and dacites in the northern Talkeetna Mountains, where they determined a paleolatitude of 76 ± 10°. The reliability of the determinations is supported by successful fold tests, consistency of reversals, and measurements of the magnetization's thermal stability. In the southern Talkeetna Mountains, Eocene volcanic rocks along the southern boundary of the Peninsular terrane yielded a paleolatitude of 80 ± 9° (Panuska and Stone, 1985a).

In a transect from Lake Clark to Iliamna Lake, Coe and others (1985) and Thrupp and Coe (1984, 1986) determined paleolatitudes of early Tertiary volcanic rocks that overlap the Peninsular terrane. Near Lake Clark, one group of lava flows dated at about 66 Ma, gave a paleolatitude of 63 ± 9°, which is 9 ± 11° lower than predicted. Minor deformation of the Lake Clark area precluded a successful fold test, but the consistency of reversals test was met. Near Hagemeister Island in Bristol Bay, Globerman and Coe (1984a, b) determined a paleolatitude similar to the one near Lake Clark. The latest Cretaceous (68 Ma) volcanic rocks near Hagemeister Island yielded a paleolatitude of 65 ± 4° and a latitude anomaly of 9 ± 7°. The islands of northern Bristol Bay are not considered part of the Peninsular terrane, but the nearly identical paleomagnetic poles from coeval volcanic sequences of the two regions indicate that the two areas have not significantly moved relative to each other since 66 Ma.

Small northward displacements approaching the magnitudes of the confidence limits are implied by the Lake Clark and Bristol Bay results, in contrast to the small southward displacement that was determined in the Talkeetna Mountains transect. Because most of the studies yielded α_{95} confidence limits of about 9°, apparent differences in paleolatitude between those areas are probably not significant. In addition, the Cantwell Formation and the volcanic rocks of Lake Clark and the northern Talkeetna Mountains appear to be part of a Late Cretaceous and early Tertiary magmatic complex that overlaps the boundaries between Wrangellia, Jurassic and Cretaceous flysch, and the Peninsular terrane. Taken as a whole, the data indicate no significant change of latitude of southern Alaska relative to North America since 68 to 55 Ma, at least within current confidence limits of about 9°.

A significant counterclockwise rotation of southern Alaska can be inferred from the distribution of Late Cretaceous and early Tertiary paleomagnetic poles (Fig. 2). The declination anomalies vary from 29 to 54° in the counterclockwise sense when the Alaskan poles are compared with the appropriate reference poles (Coe and others, 1985; Hillhouse and others, 1985). Middle Eocene and Oligocene lavas near Lake Clark give no significant anomalies in declination, so the rotation occurred between 66 and 44 Ma (Thrupp and Coe, 1986).

In contrast to the paleomagnetic evidence provided by volcanic rocks, results from Upper Cretaceous (Maastrichtian) and lower Tertiary sedimentary rocks indicate that as late as 75 to 60 Ma the Peninsular terrane and Wrangellia were about 3,000 km south of their present positions relative to the craton. These results were obtained from the MacColl Ridge Formation near McCarthy (Panuska, 1985), the Tolstoi Formation on the western Alaska Peninsula (Stone and Packer, 1979; Stone and others, 1982), and the Chickaloon Formation in the Matanuska Valley (Stone, 1984). No consistent rotation of the region is discernible from the paleomagnetic poles. If, according to Panuska (1985), the major poleward movement of Wrangellia occurred after Maastrichtian time, then emplacement of the terrane by Eocene time would require relative plate velocities greater than 24 cm/yr. As an alternative to this unusually rapid velocity, he proposed that MacColl Ridge is separated from the Eocene volcanic rocks by an unrecognized suture.

In a review of results from Late Cretaceous and early Tertiary strata, Coe and others (1985) discussed the discrepancy between determinations of high paleolatitudes from the volcanic rocks and the unusually low paleolatitudes from the sedimentary rocks. They concluded that the magnetization of Tolstoi Formation is probably contaminated by strong secondary components of magnetization. The Chickaloon and MacColl Ridge Formations gave results that passed the fold test and the reversal test, so the paleomagnetic data appear to be free of magnetic overprints. However, systematically low inclinations are sometimes found in sedimentary rocks due to compaction and settling of the magnetic grains during deposition. This mechanism might explain the very low paleolatitudes from the Chickaloon and MacColl Ridge studies, because the anomalies are similar to inclination errors observed in redeposition experiments with sediments. Because the inclinations measured in Late Cretaceous and early Tertiary volcanic rocks of the Peninsular and Wrangellia terranes are consistently steeper than the inclinations of nearly coeval sedimentary rocks, and volcanic rocks are generally acknowledged as superior recorders of the ambient magnetic field, we are skeptical of the paleolatitude determinations from the Chickaloon and MacColl Ridge Formations.

Western Alaska

The few paleomagnetic studies made in the Kuskokwim Mountains region indicate that Paleozoic rocks of western Alaska have not moved great distances in latitude relative to the craton. Karl and Hoare (1979) reported a paleomagnetic pole from volcanic rocks of possible Permian age near Nuyakuk Lake, 100 km north of Dillingham. They collected a small number of specimens from nine sites in a gently dipping, fault-bounded block of basalt flows that did not permit a fold test. All sites gave field directions of reversed polarity. The Permian age of those volcanic rocks is not supported by direct evidence from fossils, and the rocks might be as young as Late Triassic. However, exclusively reversed field directions are to be expected if the magnetization was acquired during the long reversed-polarity interval of the Early Permian. The resultant paleomagnetic pole is indistinguishable from the Permian pole for stable North America. If the magnetization is actually as young as Late Triassic, then the results indicate a poorly resolved paleolatitude anomaly of 8 ± 9° and a counterclockwise rotation of about 40°. Regardless of the age uncertainty, post-Triassic northward drift of the region is minor compared to the displacements indicated for Wrangellia and the Peninsular terrane.

Upper Paleozoic rocks of the Nixon Fork terrane also reveal no statistically significant displacement in latitude relative to the craton (Plumley, 1984). In the Medfra Quadrangle, Plumley obtained useful paleomagnetic results from the Telsitna Formation (Middle and Upper Ordovician) and the Novi Mountain Formation (Lower Ordovician) after he applied thermal demagnetization treatments. The treatments revealed several components of magnetization: a high-temperature component that showed a slight decrease in angular dispersion when the bedding corrections were applied, and lower-temperature secondary components that were acquired after folding. The high-temperature component probably reflects the magnetic field at the time of deposition and indicates no significant paleolatitude anomaly compared to the expected value as calculated from a small set of cratonic poles. A large clockwise rotation is indicated by the anomalous declination of the mean paleomagnetic direction.

Cretaceous and early Tertiary paleomagnetic poles from western Alaska generally agree with poles from coeval volcanic sequences in the Peninsular terrane, the Jurassic and Cretaceous flysch belt, and Wrangellia. In the Nixon Fork terrane, Plumley's (1984) paleomagnetic study of the Paleocene Nowitna volcanic unit showed no significant displacement of the region, but his collection consisted of samples from only six cooling units. The confidence limit on this Paleocene pole encloses the sampling site, so no conclusion can be drawn regarding possible rotation of the region. Near Ohogamiut Village, about 80 km northwest of Bethel, Lower Cretaceous volcaniclastic rocks were sampled by Globerman and others (1983). The resultant magnetic directions yielded an inconclusive fold test, although application of the tilt corrections slightly increased the angular dispersion of directions. Although Globerman and his coauthors did not explicitly rule out an Early Cretaceous age of magnetization, they favored a Late Cretaceous remagnetization of the Ohogamiut tuffs. If the true age of the overprint is Late Cretaceous, then a paleolatitude anomaly of 7 ± 10° and a substantial counterclockwise rotation are implied (Coe and others, 1985).

From late Paleozoic paleomagnetic poles from western Alaska, we infer that Wrangellia and probably the Peninsular terrane were at latitudes at least 25° lower than those of the western Alaska terranes in Late Triassic time. Across western and south-central Alaska, the general concordance of paleomagnetic poles from Paleocene volcanic rocks indicates that the gap had closed and relative northward drift had ceased by 65 to 55 Ma. Block rotations occurred between the Paleozoic terranes of western Alaska before the Paleocene, as indicated by the discordant magnetic declinations of the Nixon Fork terrane and the Nuyakuk Lake volcanic rocks. After latest Cretaceous time (68 Ma), a consistent counterclockwise rotation of 30 to 50° affected possibly the entire region between the Kaltag fault and the southern margin of the Peninsular terrane.

Chugach and Prince William terranes

The Chugach terrane (Plafker and others, this volume, Chapter 12) makes up a large part of southern Alaska, but only a few pilot studies have been made of the terrane's paleomagnetism. Stone and Packer (1979) reported results from two sites in the Shumagin Formation of probable Late Cretaceous age at Nagai Island. Sedimentary rocks of similar age and character as the Shumagin Formation were sampled at the east shore of Kodiak Island in the Kodiak Formation (Stone and others, 1982). The mean paleolatitudes of the three sites range from 6°N to 32°N, substantially lower than the predicted value of 75°N from the North American reference. When the magnetic directions from these three sites are corrected for tilt of the bedding, the angular dispersion increases, and the spread in paleolatitude between the sites increases as well. Therefore, the magnetizations are probably contaminated by a post-deformational component, and the low paleolatitude determinations might not be valid.

The only other study of Late Cretaceous rocks in the Chugach terrane is on Resurrection Peninsula near Seward where Hillhouse and Grommé (1977) sampled one site in pillow basalt and two sections in the sheeted dike complex of the Valdez(?) Group. Correcting the magnetic directions for tilt of the pillow basalts and for tilt of pillow screens within the dike complex reduced the overall scatter of directions and gave a mean paleolatitude of 51 ± 10°. This value implies about 25° of northward drift relative to the craton since the Late Cretaceous. Grommé and Hillhouse (1981) obtained a paleolatitude anomaly of similar magnitude from a study of the La Perouse and Astrolabe gabbro plutons in the southeastern part of the Chugach terrane. Recent isotopic determinations from gabbro at La Perouse indicate that it is 28 m.y. old (Loney and Himmelberg, 1983), which reduces our confidence in the validity of Grommé and Hillhouse's (1981) paleolatitude determination. To reach its present position, the La Perouse body would have to have been translated northward at twice the Pacific plate rate (Plafker, 1984). Undetected tilt of the gabbro bodies might explain their apparently low paleolatitude values.

The Prince William terrane, which makes up the southern continental margin of Alaska, shows evidence of substantial northward drift in rocks as young as early Tertiary. The most convincing evidence comes from the southern shore of Kodiak Island, where the Paleocene Ghost Rocks Formation of Moore and others (1983) has been studied by Plumley and others (1982, 1983). Pillow basalts of the Ghost Rocks were sampled at Kiliuda and Alitak Bays. The results have high reliability, as indicated by positive fold tests at both sites and a positive reversal test at Kiliuda Bay. The paleomagnetic data indicate that in Paleocene time the Ghost Rocks were 25 ± 7° south of their present position relative to continental North America. Stone and others (1982) obtained larger paleolatitude anomalies from the sedimentary part of the Ghost Rocks Formation (45 ± 9°) and from the Eocene to Oligocene Sitkalidak Formation (32 ± 19°) on Kodiak

Island. They also reported results from the Narrow Cape Formation, showing that northward drift of the terrane has been only 6 ± 8° since Late Miocene time.

The paleomagnetic data from Paleocene and Late Cretaceous volcanic rocks indicate that at that time a latitude gap of about 25° separated the Ghost Rocks and volcanic rocks of the Resurrection Peninsula from the Wrangellia and Peninsular terranes. The gap subsequently might have been closed by strike-slip motion along the Border Ranges fault. Moore and others (1983), however, argued that plutons cross the fault and tie the Chugach and Peninsular terranes together after Paleocene time; if so, the Border Ranges fault is an unlikely mechanism for closing the latitude gap. Alternatively, Coe and others (1985) suggested that the emplacement of the far-travelled volcanic rocks might have occurred by cumulative slip along many faults in southern Alaska. We should stress that the Chugach and Prince William terranes have been sampled for paleomagnetism only in reconnaissance, primarily within fault-bounded igneous rocks near the southern margins of the terranes. Because these terranes are possibly melanges of off-scraped sediment and obducted oceanic crust, the large-scale translations may have involved only a few blocks now embedded within the terranes. This explanation eliminates the problem of requiring a major zone of convergence of Tertiary age between the Chugach terrane and the mainland.

Alexander terrane

The Alexander terrane of southeastern Alaska (Gehrels and Berg, this volume) has a distinctive Paleozoic stratigraphy that sets it apart from neighboring terranes in British Columbia (Berg and others, 1972; Jones and others, 1972). Early speculations regarding possible northward displacement of the Alexander terrane were stimulated by a study of Permian fusilinid faunas by Monger and Ross (1971), who recognized a pattern in which fusilinids of "Tethyan" affinity in the Cache Creek region are sandwiched between belts containing fauna that are more typical of North America. They postulated large-scale northward strike-slip motion of the outer coastal belt, which includes the Alexander terrane, as one of several explanations for the anomalous distribution of fusilinids. As suggested by Hamilton (1969), the presence of Tethyan faunas in western North America could be attributed to the accretion of exotic blocks from the proto-Pacific region. Jones and others (1972) favored strike-slip motion of the Alexander terrane on stratigraphic and lithologic grounds, noting similarities between the Alexander terrane and coeval rocks in northern California.

Paleomagnetic studies by Van der Voo and others (1980) further corroborated the evidence for northward displacement of the Alexander terrane. They sampled a thick section of sedimentary and volcanic rocks ranging in age from Late Ordovician to Late Carboniferous on the west side of Prince of Wales Island. After demagnetization treatments were applied, useful results were obtained from the Descon Formation (Middle and Upper Ordovician), Wadleigh Limestone (Devonian), Port Refugio Formation (Upper Devonian), Peratrovich Formation (Lower Carboniferous), and Ladrones Limestone and Klawak Formation (Upper Carboniferous). Application of tilt corrections significantly reduced the directional scatter of some of the Devonian and Ordovician units, indicating that the magnetization pre-dated folding. The Wadleigh Limestone exhibited consistently antiparallel directions, which passed the reversal test for the complete removal of secondary components. The dominant group of directions, which were inclined shallowly to the east, were chosen to be of reversed polarity.

When compared to coeval reference poles, the Alexander poles indicated movement to higher latitudes of 10 to 15° and about 25° of counterclockwise rotation relative to North America since the Late Carboniferous. The optimal fit of the Alexander poles to the North American apparent polar wander curve was obtained by having the original position of the Alexander terrane near northern California, in close agreement with the hypothesis of Jones and others (1972).

However, a controversy has arisen concerning the reference poles used by Van der Voo and others (1980) in reconstructing the paleoposition of the Alexander terrane. The controversy stems from the difference between late Paleozoic poles from the interior of North America and coeval poles from coastal New England and the Canadian Maritime provinces. Van der Voo and Scotese (1981) and Kent (1982) accounted for the difference by proposing northward drift of the New England block (Acadia) relative to the craton. Other workers argued that the difference in poles is due to Permian remagnetization of the cratonic rocks, because Late Carboniferous and Devonian poles lie close to the Permian pole (Roy, 1982; Roy and Morris, 1983). A recent study by Kent and Opdyke (1985) indicates that the Carboniferous Mauch Chunk Formation of Pennsylvania is contaminated by a Permian component of magnetization, and that when the overprint is removed, the Mauch Chunk paleolatitude is not significantly different from coeval paleolatitudes of Acadia. Irving and Strong (1984, 1985) also found no evidence of an Acadian displacement in their study of Lower Carboniferous rocks in Newfoundland. Revision of the Carboniferous and Devonian poles from the interior of North America is underway, and the paleomagnetic evidence for the displacement of the Alexander terrane must be reconsidered. If the polarity that Van der Voo and others (1980) assigned to the Alexander magnetic directions is correct, then the paleomagnetic evidence favors the origin of the Alexander terrane near its present latitude relative to the craton.

In Keku Strait between Kuiu and Kupreanof Islands, the Alexander terrane is capped by Upper Triassic rocks, including the Hound Island Volcanics. Hillhouse and Grommé (1980) reported paleomagnetic results from the Hound Island Volcanics, a formation consisting of basaltic pillow lava, pillow breccia, and aquagene tuff. Their results show good reliability, as indicated by successful fold and reversal tests. Thermal demagnetization experiments revealed magnetizations having high thermal stability. The paleolatitude of the Hound Island Volcanics does not differ significantly from the predicted latitude on the basis of Triassic and Early Jurassic poles from the interior of North America. However, the Hound Island paleolatitude is significantly higher than the values obtained from coeval strata in the nearby Stikine terrane of British Columbia. Interpretation of paleomagnetic results from Triassic volcanic rocks of the Stikine terrane suggests that the block has moved about 15° northward relative to the craton (Monger and Irving, 1980; Irving and others, 1980). As with the Paleozoic rocks, the validity of the reference poles in the Triassic rocks has been called into question. Gordon and others (1984) and May and Butler (1986) have argued that the apparent displacement of the Stikine terrane is an artifact due to improper positioning of the Late Triassic (Carnian-Norian) reference pole. Nevertheless, additional evidence of northward drift of coastal British Columbia comes from studies by Irving and others (1985) of middle Cretaceous plutons of the southern Coast Plutonic Complex. Their results imply that a composite block, including part of Wrangellia and the Stikine terrane, was displaced about 2,400 km northward and rotated clockwise after 90 Ma. Because the Stikine terrane lies between the craton and the Alexander terrane, the apparent lack of displacement of the Alexander terrane is puzzling.

As with Wrangellia, the polarity of the Alexander paleomagnetic poles cannot be selected with certainty, and it is possible that the terrane has moved from an original position in the southern hemisphere. For this option, normal polarity would be assigned to the shallow eastward directions from the Paleozoic rocks, and reversed polarity would be assigned to the steeply inclined, southwestward directions from the Triassic volcanic rocks. Under the southern option the terrane would move about 50° to the south following deposition of the Devonian Port Refugio Formation and then move rapidly northward to a position 85° higher in latitude in post-Triassic time. The southern option also requires a net rotation of about 160° about a vertical axis to be in accord with the Paleozoic declinations of the Alexander terrane. Moving the Alexander terrane to the southern hemisphere has the advantage of getting the terrane out of the way of the northward-moving Stikine terrane. Compared to the northern hemisphere option, however, the southern option requires much larger displacements and more changes in the direction of transport.

Recently, Panuska and Stone (1985b) obtained evidence in support of the southern hemisphere option from the Pybus Formation, which was deposited during the Permo-Carboniferous Reversed-Polarity Superchron. If the magnetization of the Pybus Formation is indeed of Permian age, then the results would require location of the Alexander terrane in the southern hemisphere. However, the possibility of remagnetization cannot be ruled out, because Panuska and Stone could not apply a conclusive fold test to their Pybus collection. More corroboration of the Permian pole from the Alexander terrane thus is needed to prove the validity of the southern hemisphere option.

Arctic Alaska

The oil boom in northern Alaska fostered several paleomagnetic investigations of the Brooks Range (Moore and others, this volume), mainly to test for large-scale counterclockwise rotation of the Arctic Alaska block. According to the rotation hypothesis, originally proposed by Carey (1955) and later advanced by Tailleur (1973) and Grantz and others (1979), northern Alaska is interpreted as a continental fragment that rifted from the Canadian Arctic islands. Presumably, sea-floor spreading created the Canada Basin during the late Mesozoic as Arctic Alaska rotated counterclockwise relative to North America. If the rotation hypothesis is correct, Paleozoic paleomagnetic poles of northern Alaska should be displaced southeast of the North American cratonic poles.

The first paleomagnetic test of the hypothesis, reported by Newman and others (1979), was attempted in the Brooks Range. Newman and coworkers sampled Devonian, Carboniferous, and Permian sedimentary rocks in thrust sheets from Cape Lisburne to the Arctic National Wildlife Refuge. Their preliminary analysis of the data apparently supported the argument for consistent counterclockwise rotation of the Brooks Range thrust sheets. Results of reliability tests, such as the fold test, were not presented. Hillhouse and Grommé's (1983) subsequent examination of Newman and others' unpublished data showed several problems with the original interpretation. In particular, they found that the distribution of Mississippian paleomagnetic poles, mainly from the Lisburne Group, clustered near the Cretaceous pole for central North America before corrections were made for tilt of the bedding. Application of the tilt corrections increased the overall dispersion of mean directions of the Brooks Range sites, indicating the retention of a post-deformational magnetic overprint. At most sites the angular dispersion of directions was so large that the "consistency of reversals" test could not be applied.

Additional sampling by Hillhouse and Grommé (1982b, 1983) confirmed the presence of a magnetic overprint of widespread extent in the central and eastern Brooks Range. They sampled the Kanayut Conglomerate (Upper Devonian and Lower Mississippian[?]) at 11 sites distributed from the Arctic Quadrangle to the Killik River (Fig. 3). The Kanayut site directions failed the fold test conclusively, despite attempts to remove secondary components by alternating field and thermal demagnetization methods. The overprint yielded a mean paleomagnetic pole that lies close to the Cretaceous reference pole for North America. Deep burial and subsequent uplift of the Brooks Range thrust sheets apparently reset the magnetization, precluding a successful test of the rotation hypothesis.

Oriented cores from exploratory wells on the North Slope are possibly free of the magnetic overprint that affects the Brooks Range. Hillhouse and Grommé (1983) tested a 10-m, fully oriented core from the East Simpson No. 2 test well near the Arctic coast in the National Petroleum Reserve. From a depth of 2,263 m, the drilling crew recovered a core of reddened argillite, believed to be part of the eroded surface on which Mississippian sandstone was deposited. The magnetization of the core is carried by hematite that probably formed by oxidation during deposition of the Mississippian sediments. The paleomagnetic pole from the reddened argillite is located east of Japan, in general agreement with Carey's predicted 30° rotation, which assumed a rotation

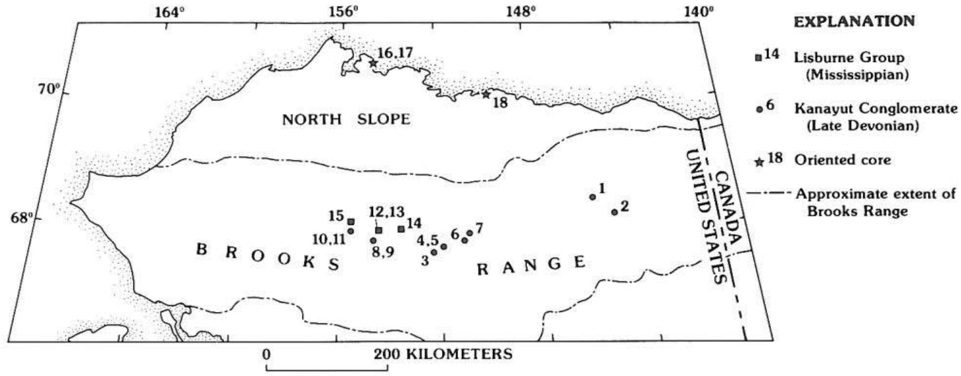

Figure 3. Locations of paleomagnetic studies in northern Alaska. 1–15, sedimentary rocks that were remagnetized after folding (Hillhouse and Grommé, 1983); 16–17, oriented cores from exploratory bore-holes in the National Petroleum Reserve (Hillhouse and Grommé, 1983); 18, two oriented cores from the Kuparuk River Formation near Prudhoe Bay (Halgedahl and Jarrard, 1987).

axis in central Alaska. Due to uncertainties in the age of magnetization and in the accuracy of the down-hole orientation procedure, Hillhouse and Grommé (1983) considered the conclusions of the study tentative.

Halgedahl and Jarrard (1987) conducted a more reliable test of the Arctic rotation hypothesis on oriented cores from two ARCO wells located in the Kuparuk River oil field on the North Slope. They obtained a paleomagnetic pole from Lower Cretaceous sedimentary rocks of the Kuparuk River Formation. The data are compatible with a model that calls for about 70° of counterclockwise rotation of Arctic Alaska about a pole of rotation in the Mackenzie River delta. The model places the North Slope region and Chukotka (U.S.S.R.) against the Canadian Arctic Islands prior to 130 Ma, when rifting began to form the Canada basin.

RELATIVE PLATE MOTIONS AND THE ACCRETION OF ALASKA

The literature concerning the paleomagnetism of Alaskan terranes has grown rapidly since 1975. Explaining every anomalous paleomagnetic result in terms of terrane movements leads to a bewildering sequence of displacements, often contradictory to other paleomagnetic studies and to geologic evidence (Plafker and Berg, this volume, Chapter 33). Our approach is to winnow the data, highlighting the better-substantiated paleomagnetic observations, mainly from studies of volcanic rocks, and to fit those observations with a plate-tectonic model for Alaska. We can distill three chief observations from the paleomagnetic literature of Alaska:

1. Wrangellia and the Peninsular terrane were separated from central Alaska by a gap in latitude of at least 25° in the early Mesozoic. By at least 55 Ma, the gap was closed by northward drift of Wrangellia and the Peninsular terrane.

2. In Late Cretaceous and Paleocene time, volcanic complexes in the southern parts of the Prince William and Chugach terranes were 25° south of the Alaskan margin.

3. After 68 Ma and before 44 Ma, central and western Alaska rotated 30 to 50° counterclockwise, presumably about a hinge line near 146°W.

Our goal is to fit these three observations from paleomagnetism into a plate-tectonic model that incorporates motions of oceanic plates in the Pacific and sea-floor spreading in the Arctic, which are the major tectonic forces that have shaped Alaska. Since at least 100 Ma, vast areas of sea floor have been subducted beneath the northern Pacific continental margin, as interpreted from the pattern of magnetic anomalies in the Gulf of Alaska. Hence, subduction and sea-floor spreading provide the mechanism for bringing terranes such as Wrangellia into Alaska. The past motions of the oceanic plates are difficult to reconstruct, because much of the older sea floor has been subducted and the early motion of the Pacific plate relative to North America is poorly known. Nevertheless, models of the now-vanished oceanic plates can be reconstructed from the magnetic anomalies of the Pacific basin, if it is assumed that sea-floor spreading has been symmetrical about the ridges. North America–Pacific plate motions can be estimated by following the circuit of spreading centers from the Atlantic Ocean through Antarctica to the Pacific Ocean (Atwater and Molnar, 1973), or by using the hot-spot reference frame (Engebretson, 1982; Engebretson and others, 1985). The assumptions behind both methods of reconstruction are subject to error, so that the positions of ancient spreading centers and the relative plate motions are imprecisely determined.

Nevertheless, oceanic plate reconstructions, such as the models presented by Stone and others (1982) or Wallace and Engebretson (1984) for the Alaska margin, offer a reasonable mechanism for the emplacement of Wrangellia, the Peninsular terrane, and the Prince William terrane. For example, prior to 150 Ma, Wrangellia might have been riding the Farallon plate in the southwest Pacific region (Engebretson, 1982). By middle Jurassic time, Wrangellia and the Peninsular terrane had joined together. The amalgamated terrane was carried northeastward toward the North American margin, possibly colliding with the continent near Oregon in the Early Cretaceous. We believe that part of Wrangellia was in Oregon by 130 Ma, because plutons of that age intrude the Seven Devils Group and yield concordant paleolatitudes with respect to the North American reference pole (Wilson and Cox, 1980; Hillhouse and others, 1982). Also, at about 130 Ma, Arctic Alaska rifted away from the Canadian Arctic Islands as the Canada basin began to form. Engebretson and others (1985) suggested that the Farallon plate was divided about 85 Ma by a spreading center, the northern part becoming the Kula plate. If the Kula-Farallon spreading center was south of Wrangellia, then the motion of the Kula plate relative to North America would be of the proper direction and velocity to bring Wrangellia into Alaska by 55 Ma. Transcurrent faults could detach Wrangellia from the mainland and slip it northward, leaving splinters of the terrane along the continental margin at Vancouver Island, Queen Charlotte Island, and southern Alaska. At that time, the zone of dextral shear probably extended east to the Tintina fault, causing northward drift of the Stikine terrane relative to the cratonic margin.

Our model for the accretion of Wrangellia and the Peninsular terrane is consistent with the timing of deformation and plutonism in the Jura-Cretaceous flysch terrane of south-central Alaska, which was the zone of convergence between Wrangellia and the mainland. Intense deformation of the flysch and obduction of smaller terranes such as Chulitna occurred after 100 Ma, because the youngest flysch beds are Cenomanian in age (Csejtey and others, 1982). Large-scale shortening of the flysch basin is indicated by the chaotic structure and penetrative deformation of the deposits. Relative motions between Wrangellia, the flysch, and the Nixon Fork terrane are constrained by the Alaska Range belt of plutons, which cuts across the terrane boundaries and the isoclinal folds within the flysch. The plutons were emplaced between 75 and 55 Ma (Reed and Lanphere, 1973; Lanphere and Reed, 1985).

Paleomagnetic evidence against post-Triassic displacement of the Alexander terrane remains an enigma, and cannot be simply explained by the oceanic plate model. The Tethyan fauna of the Cache Creek Group and the low paleolatitudes of the Coast Plutonic Complex imply that the Alexander terrane is out of place. The paleomagnetism of the Alexander terrane clearly warrants further study.

As preserved in volcanic rocks, the Paleocene and Early Eocene paleomagnetic record of Alaska constrains northward movement of the block between the Tintina fault and the Chugach terrane to have ended by 55 Ma, providing the backstop for the exotic southern blocks. The velocity and direction of the Kula plate are easily sufficient to close the 25° latitude gap between Paleocene volcanic rocks of the Prince William terrane and the previously accreted margin of Alaska, according to Wallace and Engebretson's (1984) model. Relative motion of the Kula plate accelerated in the interval 56 to 43 Ma, reaching a rate of 200 km/m.y. near the Kenai Peninsula. After the demise of the Pacific-Kula ridge at 43 Ma, when the Pacific plate began to subduct beneath Alaska, the rate of motion between North America and the Pacific plate was about 40 km/m.y. Therefore, most of the northward impetus was provided by the Kula plate in a northeast direction, with the Pacific plate adding a small component of slip along the British Columbia–Alaska margin after 43 Ma. Our model implies that the Paleocene volcanic rocks of the Prince William terrane originated in the Pacific Ocean far from the North American continental margin. The volcanic rocks were probably decoupled from the sedimentary rocks of the Prince William terrane, because the sediments were derived from a continental source (Plafker and others, this volume, Chapter 12). The volcanic rocks might be fragments of oceanic crust that collided with a sedimentary apron along the British Columbia–southeastern Alaska margin. This scenario solves the problem of the enigmatic suture between the Chugach and Peninsular terranes.

The third observation, that western Alaska rotated counterclockwise after 55 Ma, can be explained as a consequence of continental deformation at the time of sea-floor spreading in the North Atlantic and the Labrador Sea (Grantz, 1966; Patton and Tailleur, 1977). Spreading in the Labrador Sea between Greenland and North America was active from the Late Cretaceous to the early Oligocene (Srivastava, 1978), whereas spreading in the North Atlantic and Eurasian basin has occurred since 90 Ma (Pitman and Talwani, 1972). The opening of these basins requires overlap or compression of continental crust along the Eurasia–North America boundary from 70 to 50 Ma. The boundary is generally assumed to be in the northeast U.S.S.R., but it is not clearly defined. Continental overlap might have been accommodated by deformation in the Bering Sea region, which forced western Alaska to the southeast. If so, the motion would entail rotation about a hinge line near 146°W and dextral slip along the Beringian continental margin, a proposal that is consistent with the arcuate structural trends of southwestern Alaska. Restoration of western Alaska to its original position straightens out the arcuate trends and creates a geometry similar to the model of Freeland and Dietz (1973), although opening of the Canada Basin was the main rotational mechanism of their model. Rotation of western Alaska probably ceased by 50 Ma when a change in the pole of opening of the Arctic basin eased North America–Eurasia compression (Harbert and others, 1985). Also, at that time a fragment of the Kula plate was trapped behind the growing Aleutian volcanic arc, and motion ceased along the Beringian margin (Marlow and Cooper, 1980).

CONCLUSION

The accretion of southern Alaska was apparently a two-step process, according to our analysis of the paleomagnetic data. First, Wrangellia and the Peninsular terrane collided with the Nixon Fork and Yukon–Tanana terranes during the interval 100 to 55 Ma to make up the core of Alaska. Motion of the Kula plate probably provided the impetus to finally close the latitude gap between Wrangellia and the mainland. Secondly, volcanic complexes now embedded in the southern margins of the Prince William and Chugach terranes arrived in Alaska after 55 Ma, carried first by the Kula and then by the Pacific plate. The counterclockwise rotation of southwestern Alaska most likely occurred 68 to 44 m.y. ago as the latitude gap was closing between the volcanic complexes and the mainland. The rotation of western Alaska may be the result of deformation at the boundary between North America and Eurasia at the time of sea-floor spreading in the Eurasian basin, Labrador Sea, and North Atlantic.

REFERENCES CITED

Andrews, J. A., 1985, True polar wander; An analysis of Cenozoic and Mesozoic paleomagnetic poles: Journal of Geophysical Research, v. 90, p. 7737–7750.

Atwater, T., and Molnar, P., 1973, Relative motion of the Pacific and North American plates deduced from sea-floor spreading in the Atlantic, Indian, and South Pacific Oceans, *in* Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, Stanford University, California: Stanford, California, Stanford University Publications in the Geological Sciences, v. 13, p. 136–148.

Berg, H. C., Jones, D. L., and Richter, D. H., 1972, Gravina-Nutzotin belt; Tectonic significance of an upper Mesozoic sedimentary and volcanic sequence in southern and southeastern Alaska: U.S. Geological Survey Professional Paper 800-D, p. D1–D24.

Burk, C. A., 1965, Geology of the Alaska Peninsula; Island arc and continental margin: Geological Society of America Memoir 99, part 1, 250 pp.

Carey, S. W., 1955, The orocline hypothesis in geotectonics: Proceedings of the Royal Society of Tasmania, v. 89, p. 255–288.

Coe, R. S., Globerman, B. R., Plumley, P. W., and Thrupp, G. A., 1985, Paleomagnetic results from Alaska and their tectonic implications, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the Circum-Pacific region: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 1, p. 85–108.

Cox, A., and Gordon, R. G., 1984, Paleolatitudes determined from paleomagnetic data from vertical cores: Reviews of Geophysics and Space Physics, v. 22, p. 47–72.

Csejtey, B., Jr., Cox, D. P., Evarts, R. C., Stricker, G. D., and Foster, H. L., 1982, The Cenozoic Denali fault system and the Cretaceous accretionary development of southern Alaska: Journal of Geophysical Research, v. 87, p. 3741–3754.

Duncan, R. A., 1981, Hot spots in the southern oceans; An absolute frame of reference for motion of the Gondwana continents: Tectonophysics, v. 74, p. 29–42.

Engebretson, D. C., 1982, Relative motions between oceanic and continental plates in the Pacific Basin [Ph.D. thesis]: Stanford, California, Stanford University, 211 p.

Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic plates in the Pacific basin: Geological Society of America Special Paper 206, 59 p.

Freeland, G. L., and Dietz, R. S., 1973, Rotation history of Alaskan tectonic blocks: Tectonophysics, v. 18, p. 379–389.

Globerman, B. R., and Coe, R. S., 1984a, Paleomagnetic results from Upper Cretaceous volcanic rocks in northern Bristol Bay, SW Alaska, and tectonic implications, *in* Proceedings of the Circum-Pacific Terrane Conference, Stanford University, California: Stanford, California, Stanford University Publications in the Geological Sciences, v. 18, p. 98–102.

——, 1984b, Discordant declinations from "in place" Upper Cretaceous volcanics, SW Alaska; Evidence for oroclinal bending?: Geological Society of America Abstracts with Programs, v. 16, p. 286.

Globerman, B. R., Coe, R. S., Hoare, J. M., and Decker, J., 1983, Palaeomagnetism of Lower Cretaceous tuffs from Yukon–Kuskokwim delta region, western Alaska: Nature, v. 305, p. 516–520.

Goldreich, P., and Toomre, A., 1969, Some remarks on polar wandering: Journal of Geophysical Research, v. 74, p. 2555–2567.

Gordon, R. G., 1983, Late Cretaceous apparent polar wander of the Pacific plate; Evidence for a rapid shift of the Pacific hot spots with respect to the spin axis: Geophysical Research Letters, v. 10, p. 709–712.

Gordon, R. G., Cox, A., and O'Hare, S., 1984, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous: Tectonics, v. 3, p. 499–537.

Grantz, A., 1966, Strike-slip faults in Alaska: U.S. Geological Survey Open-File Report 66–53, 82 p., 4 sheets, scale 1:63,360.

Grantz, A., Eittrem, S., and Dinter, D. A., 1979, Geology and tectonic development of the continental margin of North America: Tectonophysics, v. 59, p. 263–291.

Grommé, S., and Hillhouse, J. W., 1981, Paleomagnetic evidence for northward movement of the Chugach terrane, southern and southeastern Alaska, *in* Albert, N.R.D., and Hudson, T., eds., The U.S. Geological Survey in Alaska: Accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B70–B72.

Halgedahl, S., and Jarrard, R., 1987, Paleomagnetism of the Kuparuk River Formation from oriented drill core; Evidence for rotation of the Arctic Alaska plate, *in* Tailleur, I., and Weiner, P., eds., Alaska North Slope, volume 2: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 581–617.

Hamilton, W., 1969, Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430.

Harbert, W. P., Frei, L. S., Cox, A., and Engebretson, D. C., 1985, Relative motions between Eurasia and North America in Bering Sea region: American Association of Petroleum Geologists Bulletin, v. 69, p. 665–666.

Harrison, C.G.A., and Lindh, T., 1982, Comparison between the hot spot and geomagnetic field reference frames: Nature, v. 300, p. 251–252.

Hillhouse, J. W., 1977, Paleomagnetism of the Triassic Nikokai Greenstone, McCarthy Quadrangle, Alaska: Canadian Journal of Earth Sciences, v. 14, p. 2578–2592.

——, 1987, Accretion of southern Alaska: Tectonophysics, v. 139, p. 107–122.

Hillhouse, J. W., and Grommé, C. S., 1977, Paleomagnetic poles from sheeted dikes and pillow basalt of the Valdez(?) and Orca Groups, southern Alaska: EOS Transactions of the American Geophysical Union, v. 58, p. 1127.

——, 1980, Paleomagnetism of the Triassic Hound Island volcanics, Alexander terrane, southeastern Alaska: Journal of Geophysical Research, v. 85, p. 2594–2602.

——, 1982a, Limits to northward drift of the Paleocene Cantwell Formation, central Alaska: Geology, v. 10, p. 552–556.

——, 1982b, Cretaceous overprint revealed by paleomagnetic study in the northern Brooks Range *in* Coonrad, W. L., ed., The U.S. Geological Survey in Alaska; Accomplishments during 1980: U.S. Geological Survey Circular 844, p. 43–46.

——, 1983, Paleomagnetic studies and the hypothetical rotation of Arctic Alaska: Alaska Geological Society Journal, v. 2, p. 27–39.

——, 1984, Northward displacement and accretion of Wrangellia; New paleomagnetic evidence from Alaska: Journal of Geophysical Research, v. 89, p. 4461–4477.

Hillhouse, J. W., Grommé, C. S., and Vallier, T. L., 1982, Paleomagnetism and Mesozoic tectonics of the Seven Devils volcanic arc in northeastern Oregon: Journal of Geophysical Research, v. 87, p. 3777–3794.

Hillhouse, J. W., Grommé, C. S., and Csejtey, B., Jr., 1985, Tectonic implications of paleomagnetic poles from lower Tertiary volcanic rocks, south central Alaska: Journal of Geophysical Research, v. 90, p. 12523–12536.

Irving, E., 1979, Paleopoles and paleolatitudes of North America and speculations about displaced terranes: Canadian Journal of Earth Sciences, v. 16, p. 669–694.

Irving, E., and Irving, G. A., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana: Geophysical Surveys, v. 5, p. 141–188.

Irving, E., and Strong, D. F., 1984, Evidence against large-scale Carboniferous strike-slip faulting in the Appalachian-Caledonian orogen: Nature, v. 310, p. 762–764.

——, 1985, Paleomagnetism of rocks from Burin Peninsula, Newfoundland; Hypothesis of late Paleozoic displacement of Acadia criticized: Journal of Geophysical Research, v. 90, p. 1949–1962.

Irving, E., and Yole, R. W., 1972, Paleomagnetism and kinematic history of mafic and ultramafic rock in fold mountain belts: Ottawa, Canada Department of Energy Mines and Resources, Publications of the Earth Physics Branch, v. 42, no. 3, p. 87–95.

Irving, E., Monger, J.W.H., and Yole, R. W., 1980, New paleomagnetic evidence for displaced terranes in British Columbia, *in* Strangway, D. W., ed., The continental crust and its mineral deposits: Geological Association of Canada Special Paper 20, p. 441–456.

Irving, E., Woodsworth, G. J., Wynne, P. J., and Morrison, A., 1985, Paleomagnetic evidence for displacement from south of the Coast Plutonic Complex, British Columbia: Canadian Journal of Earth Sciences, v. 22, p. 584–598.

Jones, D. L., and Silberling, N. J., 1979, Mesozoic stratigraphy; The key to tectonic analysis of southern and central Alaska: U.S. Geological Survey Open-File Report 79-1200, 37 p.

Jones, D. L., Irwin, W. P., and Ovenshine, A. T., 1972, Southeastern Alaska; A displaced continental fragment?: U.S. Geological Survey Professional Paper 800-B, p. B211–B217.

Jones, D. L., Silberling, N. J., and Hillhouse, J., 1977, Wrangellia; A displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, p. 2565–2577.

Jurdy, D. M., 1981, True polar wander: Tectonophysics, v. 74, p. 1–16.

Karl, S., and Hoare, J. M., 1979, Results of a preliminary paleomagnetic study of volcanic rocks from Nuyakuk Lake, southwestern Alaska *in* Johnson, K. M., and Williams, J. R., eds., The U.S. Geological Survey in Alaska; Accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B74–B78.

Kent, D. V., 1982, Paleomagnetic evidence for post-Devonian displacement of the Avalon platform (Newfoundland): Journal of Geophysical Research, v. 87, p. 8709–8716.

Kent, D. V., and Opdyke, N. D., 1985, Multicomponent magnetizations from the Mississippian Mauch Chunk Formation of the central Appalachians and their tectonic implications: Journal of Geophysical Research, v. 90, p. 5371–5383.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of palaeomagnetic data: Geophysical Journal of the Royal Astronomical Society, v. 62, p. 699–718.

Lanphere, M. A., and Reed, B. L., 1985, The McKinley Sequence of granitic rocks; A key element in the accretionary history of southern Alaska: Journal of Geophysical Research, v. 90, p. 11413–11430.

Loney, R. A., and Himmelberg, G. R., 1983, Structure and petrology of the La Perouse gabbro intrusion, Fairweather Range, southeastern Alaska: Journal of Petrology, v. 24, part 4, p. 377–423.

Marlow, M. S., and Cooper, A. K., 1980, Mesozoic and Cenozoic structural trends under southern Bering Sea shelf: American Association of Petroleum Geologists Bulletin, v. 64, p. 2139–2155.

May, S. R., and Butler, R. F., 1986, North American Jurassic apparent polar wander; Implications for plate motion, paleogeography, and Cordilleran tectonics: Journal of Geophysical Research, v. 91, p. 11,519–11,544.

McElhinny, M. W., 1973, Palaeomagnetism and plate tectonics: Cambridge, Cambridge University Press, 358 p.

McElhinny, M. W., and Merrill, R. T., 1975, Geomagnetic secular variation over the past 5 m.y.: Reviews of Geophysics and Space Physics, v. 13, p. 687–708.

Merrill, R. T., and McElhinny, M. W., 1983, The earth's magnetic field; Its history, origin, and planetary perspective: New York, Academic Press, 401 p.

Monger, J.W.H., and Irving, E., 1980, Northward displacement of north-central British Columbia: Nature, v. 285, p. 289–294.

Monger, J.W.H., and Ross, C. A., 1971, Distribution of fusulinaceans in the western Canadian Cordillera: Canadian Journal of Earth Sciences, v. 8, p. 259–278.

Monger, J.W.H., Souther, J. G., and Gabrielse, H., 1972, Evolution of the Canadian Cordillera; A plate tectonic model: American Journal of Science, v. 272, p. 577–602.

Moore, J. C., and 5 others, 1983, Paleogene evolution of the Kodiak Islands, Alaska; Consequences of ridge-trench interaction in a more southerly latitude: Tectonics, v. 2, p. 265–293.

Morgan, W. J., 1972, Plate motions and deep mantle convection, *in* Shagam, R., and others, eds., Studies in Earth and space sciences: Geological Society of America Memoir 132, p. 7–22.

Newman, G. W., Mull, C. G., and Watkins, N. D., 1979, Northern Alaska paleomagnetism, plate rotation, and tectonics, *in* Sisson, A., ed., The relationship of plate tectonics to Alaskan geology and resources: Anchorage, Alaska Geological Society Symposium Proceedings, No. 6, p. C1–C7.

Packer, D. R., and Stone, D. B., 1972, An Alaskan Jurassic paleomagnetic pole and the Alaskan orocline: Nature, v. 237, p. 25–26.

——, 1974, Paleomagnetism of Jurassic rocks from southern Alaska, and the tectonic implications: Canadian Journal of Earth Sciences, v. 11, p. 976–997.

Panuska, B. C., 1985, Paleomagnetic evidence for a post-Cretaceous accretion of Wrangellia: Geology, v. 13, p. 880–883.

Panuska, B., and Macicak, M., 1986, A revised paleolatitude for the Paleocene Teklanika Volcanics, central Alaska Range, Alaska: EOS Transactions of the American Geophysical Union, v. 67, p. 921.

Panuska, B. C., and Stone, D. B., 1981, Late Palaeozoic palaeomagnetic data for Wrangellia; Resolution of the polarity ambiguity: Nature, v. 293, p. 561–563.

——, 1985a, Confirmation of the pre-50 m.y. accretion age of the Southern Alaska superterrane: EOS Transactions of the American Geophysical Union, v. 66, p. 863.

——, 1985b, Latitudinal motion of the Wrangellia and Alexander terranes and the Southern Alaska superterrane, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 1, p. 109–120.

Patton, W. W., Jr., and Tailleur, I. L., 1977, Evidence in the Bering Strait region for differential movement beneath North America and Eurasia: Geological Society of America Bulletin, v. 88, p. 1298–1304.

Pitman, W. C., III, and Talwani, M., 1972, Sea-floor spreading in the North Atlantic: Geological Society of America Bulletin, v. 83, p. 619–646.

Plafker, G., 1984, Comment on 'Model for the origin of the Yakutat block, an accreting terrane in the northern Gulf of Alaska': Geology, v. 12, p. 563.

Plumley, P. W., 1984, A paleomagnetic study of the Prince William terrane and Nixon Fork terrane, Alaska [Ph.D. thesis]: Santa Cruz, University of California, 190 p.

Plumley, P. W., Coe, R. S., Byrne, T., Reid, M. R., and Moore, J. C., 1982, Palaeomagnetism of volcanic rocks of the Kodiak Islands indicates northward latitudinal displacement: Nature, v. 300, p. 50–52.

Plumley, P. W., Coe, R. S., and Byrne, T., 1983, Paleomagnetism of the Paleocene Ghost Rocks Formation, Prince William terrane, Alaska: Tectonics, v. 2, p. 295–314.

Reed, B. L., and Lanphere, M. A., 1973, Alaska–Aleutian Range batholith; Geochronology, chemistry, and relation to circum-Pacific plutonism: Geological Society of America Bulletin, v. 84, p. 2583–2610.

Roy, J. L., 1982, Paleomagnetism of Siluro-Devonian rocks from eastern Maine; Discussion: Canadian Journal of Earth Sciences, v. 19, p. 225–232.

Roy, J. L., and Morris, W. A., 1983, A review of paleomagnetic results from the Carboniferous of North America; The concept of Carboniferous geomagnetic field markers: Earth and Planetary Science Letters, v. 65, p. 167–181.

Schwarz, E. J., Muller, J. E., and Clark, K. R., 1980, Paleomagnetism of the Karmutsen basalts from southeast Vancouver Island: Canadian Journal of Earth Sciences, v. 17, p. 389–399.

Srivastava, S. P., 1978, Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic: Geophysical Journal of the Royal Astronomical Society, v. 52, p. 313–357.

Stone, D. B., 1982, Triassic paleomagnetic data and paleolatitudes for Wrangellia, Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 73, p. 55–62.

——, 1984, Concordance and conflicts in Alaskan paleomagnetic data, *in* Proceedings of the Circum-Pacific Terrane Conference: Stanford, California, Stanford University Publications in the Geological Sciences, v. 18, p. 186–189.

Stone, D. B., and Packer, D. R., 1977, Tectonic implications of Alaska Peninsula paleomagnetic data: Tectonophysics, v. 37, p. 183–201.

——, 1979, Paleomagnetic data from the Alaska Peninsula: Geological Society of America Bulletin, v. 90, p. 545–560.

Stone, D. B., Panuska, B. C., and Packer, D. R., 1982, Paleolatitudes versus time for southern Alaska: Journal of Geophysical Research, v. 87, p. 3697–3707.

Symons, D.T.A., 1971, Paleomagnetic notes on the Karmutsen Basalts, Vancouver Island, British Columbia: Canada Geological Survey Paper 71–24, p. 11–24.

Tailleur, I. L., 1973, Probable rift origin of Canada Basin: American Association of Petroleum Geologists Memoir 19, p. 526–535.

Thrupp, G. A., and Coe, R. S., 1984, Paleomagnetism of Tertiary volcanic rocks from the Alaska Peninsula; Is the Peninsular terrane a coherent tectonic entity?: Geological Society of America Abstracts with Programs, v. 16, p. 337.

——, 1986, Early Tertiary paleomagnetic evidence and the displacement of southern Alaska: Geology, v. 14, p. 213–217.

Van der Voo, R., and Scotese, C., 1981, Paleomagnetic evidence for a large (2,000 km) sinistral offset along the Great Glen fault during Carboniferous time: Geology, v. 9, p. 583–589.

Van der Voo, R., Jones, M., Grommé, C. S., Eberlein, G. D., and Churkin, M., Jr., 1980, Paleozoic paleomagnetism and northward drift of the Alexander terrane, southeastern Alaska: Journal of Geophysical Research, v. 85, p. 5281–5296.

Wallace, W. K., and Engebretson, D. C., 1984, Relationships between plate motions and Late Cretaceous to Paleogene magmatism in southwestern Alaska: Tectonics, v. 3, p. 295–315.

Wilson, D., and Cox, A., 1980, Paleomagnetic evidence for tectonic rotation of Jurassic plutons in Blue Mountains, eastern Oregon: Journal of Geophysical Research, v. 85, p. 3681–3689.

Yole, R. W., and Irving, E., 1980, Displacement of Vancouver Island; Paleomagnetic evidence from the Karmutsen Formation: Canadian Journal of Earth Sciences, v. 17, p. 1210–1228.

Zijderveld, J.D.A., 1967, A. C. demagnetization of rocks; Analysis of results, *in* Collinson, D. W., Creer, K. M., and Runcorn, S. K., eds., Methods in paleomagnetism: New York, Elsevier, p. 254–286.

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NOTES ADDED IN PROOF

Several new studies of paleomagnetism in Alaska were published during the interval 1989–1993 as this volume was being assembled and typeset. We wish to alert readers to the additional references cited below, and we highlight some new paleomagnetic results from the Peninsular, Chugach, and Alexander terranes.

Peninsular terrane

Stamatakos and others (1989) reported paleomagnetic results from Upper Cretaceous and lower Tertiary sedimentary rocks in Matanuska Valley, which lies within the Peninsular terrane of southern Alaska. Their results from four sites in the Matanuska Formation (Upper Cretaceous) north of the Castle Mountain fault indicated that the sediments were deposited 2,800 ± 2,000 km south of the formation's present latitudinal position with respect to North America. Furthermore, the Chickaloon and Arkose Ridge Formations of early Tertiary age yielded low magnetic inclinations corresponding to relative northward movement of 1,600 ± 1,200 km. On the basis of redeposition and compaction experiments, Stamatakos and others (1989) found no tendency for these sediments to develop systematically shallow inclinations relative to the ambient magnetic field during deposition. Therefore, the paleomagnetic record from sedimentary rocks continues to support the case for unusually rapid northward movement of the Peninsular terrane during the early Tertiary. In contrast, Matanuska Valley volcanic rocks that are slightly younger than the Chickaloon and Arkose Ridge Formations yield significantly higher paleolatitudes, implying no significant drift relative to the craton after the Eocene (38.8–53.6 Ma; Panuska and others, 1990). The disparity of paleomagnetic results from volcanic versus sedimentary rocks in southern Alaska poses a problem for future research.

Chugach terrane

The Resurrection Peninsula ophiolite was sampled extensively for paleomagnetism by Bol and others (1992). The new results imply a northward latitudinal displacement of the Chugach terrane of 13° ± 9° (1,400 ± 1,000 km), about half of the displacement inferred from previously reported results. Higher confidence is placed in these new results, owing to better age control (57 Ma from U/Pb), more extensive sampling, and better structural control. As inferred from the paleomagnetic evidence, the Resurrection Peninsula ophiolite moved northward on the order of 1,000 km relative to the lower Tertiary volcanic rocks of Matanuska Valley and the Talkeetna Mountains. The ophiolite may be part of the now-extinct Kula-Farallon ridge that accreted to the Alaska margin by 45 Ma.

Alexander terrane

The paradox posed by early work on the Triassic Hound Island Volcanics has been eliminated by a more extensive study (Haeussler and others, 1992a) of the paleomagnetism of the Alexander terrane. The paradox arose from the apparent lack of post-Triassic northward displacement of the Alexander terrane in contrast with substantial displacements inferred for coeval terranes in the mountains of western British Columbia. Careful separation of magnetic components by Haeussler and others (1992b) showed the previous results to be flawed by magnetic overprints. Elimination of the overprint yielded a paleolatitude of 19.2° ± 10.3° for the Triassic volcanic rocks, suggesting that the Alexander terrane and the neighboring Wrangellia terrane shared a common latitude during the Late Triassic. Analysis of paleomagnetic data from the Pybus Formation suggests that the Alexander terrane was in the northern hemisphere during the Permian.

ADDITIONAL REFERENCES

Bol, A. J., Coe, R. S., Gromme, C. S., and Hillhouse, J. W., 1992, Paleomagnetism of the Resurrection Peninsula, Alaska: Implications for the tectonics of southern Alaska and the Kula-Farallon ridge: Journal of Geophysical Research, v. 97, p. 17213–17232.

Haeussler, P., Coe, R. S., and Onstott, T. C., 1992a, Paleomagnetism of the Late Triassic Hound Island Volcanics: Revisited: Journal of Geophysical Research, v. 97, p. 19617–19639.

Haeussler, P.J., Coe, R. S., and Renne, P., 1992b, Paleomagnetism and geochronology of 23 Ma gabbroic intrusions in the Keku Strait, Alaska, and implications for the Alexander terrane: Journal of Geophysical Research, v. 97, p. 19641–19649.

Harbert, W., 1990, Paleomagnetic data from Alaska: Reliability, interpretation, and terrane trajectories: Tectonophysics, v. 184, p. 111–135.

Panuska, B. C., Stone, D. B., and Turner, D. L., 1990, Paleomagnetism of Eocene volcanic rocks, Talkeetna Mountains, Alaska: Journal of Geophysical Research, v. 95, p. 6737–6750.

Stamatakos, J. A., Kodama, K. P., Vittorio, L. F., and Pavlis, T. L., 1989, Paleomagnetism of Cretaceous and Paleocene sedimentary rocks across the Castle Mountain fault, south central Alaska: American Geophysical Union Geophysical Monograph Series, v. 50, p. 151–177.

Stone, D. B., and McWilliams, M. O., 1989, Paleomagnetic evidence for relative motion in western North America, *in* Ben-Avraham, Z., ed., Evolution of the Pacific Ocean Margins: Oxford, Oxford University Press, p. 53–72.

Wittbrodt, P. R., Stone, D. B., and Turner, D. L., 1989, Paleomagnetism and geochronology of St. Matthew Island, Bering Sea: Canadian Journal of Earth Sciences, v. 26, p. 2116–2129

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