

Late Cretaceous paleogeography of Wrangellia: Paleomagnetism of the MacColl Ridge Formation, southern Alaska, revisited

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ABSTRACT

Volcanic and sedimentary strata of the Late Cretaceous MacColl Ridge Formation were sampled and demagnetized to reevaluate the paleomagnetically derived paleolatitude of the allochthonous Wrangellia terrane. Characteristic directions from 15 sites representing ~750 m of the MacColl Ridge Formation (80 Ma) reveal a reversed-polarity primary magnetization yielding a paleomagnetic pole at 126°E, 68°N, $A_{95} = 9^\circ$. Comparison of this pole with the Late Cretaceous reference pole for North America indicates $15^\circ \pm 8^\circ$ of latitudinal displacement (northward) and $33^\circ \pm 25^\circ$ of counterclockwise rotation. In contrast to previously reported low paleolatitudes ($32^\circ \pm 9^\circ$ N) for the MacColl Ridge Formation, these new results place the Wrangellia terrane at a moderate paleolatitude ($53^\circ \pm 8^\circ$ N) in the Late Cretaceous.

Keywords: Alaska, paleomagnetism, terranes, Wrangellia, paleogeography.

INTRODUCTION

Although there is general agreement that much of the northwest Cordillera, including southern Alaska, is composed of allochthonous terranes, the nature and timing of terrane accretion and subsequent tectonic modification of the accreted margin remain equivocal (e.g., Cowan et al., 1997). The central question is whether allochthonous terranes of

southern Alaska and western Canada were at relatively low paleolatitudes, offshore present-day Baja California, or much closer to their present latitudinal positions offshore present-day British Columbia, Oregon, and Washington, during the late Mesozoic and early Tertiary.

A critical and often cited paleomagnetic result important to the debate about the Meso-

zoic paleogeography of the Cordillera (e.g., Umhoefer, 1987; Irving et al., 1996) was derived from sedimentary strata of the Late Cretaceous MacColl Ridge Formation (Panuska, 1985). The MacColl Ridge Formation is particularly significant to paleogeographic studies because it was deposited on rocks of the Wrangellia composite terrane. The Wrangellia composite terrane is a subcontinent-scale amalgamation of allochthonous crustal fragments (Fig. 1A), including the Peninsular, Wrangellia (at least the fragments now exposed in Alaska), and Alexander terranes, that have shared a common tectonic history since the end of the Paleozoic (Plafker and Berg, 1994). Fragments of Wrangellia are also exposed along the northern Cordillera in western Canada (Fig. 1A). Paleomagnetic results from Panuska (1985) place the Wrangellia composite terrane more than 4000 km south of its present position in the Late Cretaceous. The reliability of the paleomagnetic results from the MacColl Ridge Formation has been ques-

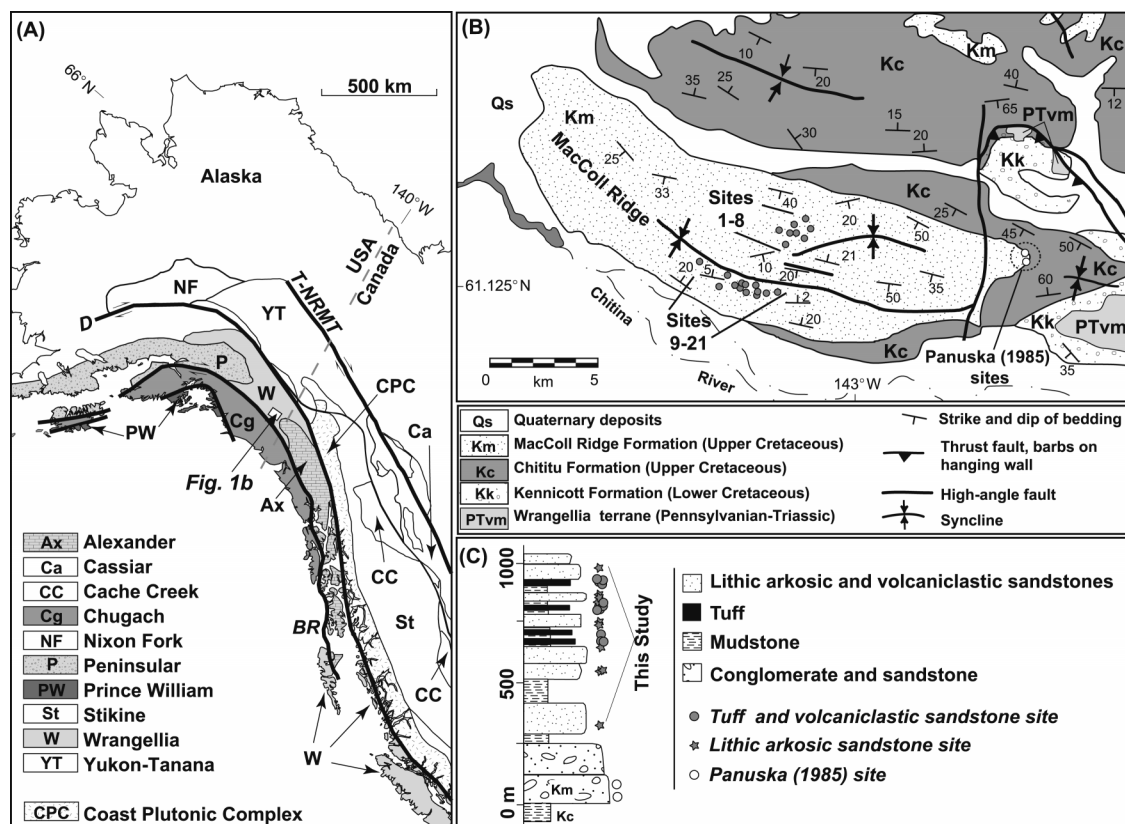


Figure 1. A: Map of northwestern Cordillera showing major terranes (adapted from Umhoefer, 1987). Terrane-bounding fault systems, Border Ranges (BR), Denali (D), and Tintina-Northern Rocky Mountain Trench (T-NRMT) are shown as heavy black lines. B: Geologic map of MacColl Ridge, Alaska, after Miller and MacColl (1964) and MacKevett (1978), showing paleomagnetic site locations. C: Generalized stratigraphic column of MacColl Ridge Formation (Km) and uppermost Chititu Formation (Kc) after Trop et al. (1999), showing stratigraphic distribution of paleomagnetic sites.

tioned, however, because of a high sample rejection rate (75% of the original demagnetized samples were deemed unusable), small sample size (20 specimen directions defined the formation mean), poor demagnetization quality (alternating fields to a peak of 40 mT), and possible inclination error (e.g., Hillhouse and Coe, 1994; Butler et al., 1997).

A recent stratigraphic study of the MacColl Ridge Formation documents previously unreported crystal vitric tuffs within the upper part of the section (Trop et al., 1999). These interbedded tuffs and associated volcanoclastic sandstones provide ideal lithologies to reevaluate the paleomagnetism of the MacColl Ridge Formation because volcanic strata typically carry a stable remanence, not susceptible to inclination error. These new paleomagnetic results from the MacColl Ridge Formation redefine the paleogeographic position of the MacColl Ridge Formation in the Late Cretaceous and by inference delimit northward transport of the Wrangellia composite terrane in the Late Cretaceous and early Tertiary.

GEOLOGIC SETTING AND SAMPLING

The MacColl Ridge Formation represents the stratigraphically youngest unit of a 7-km-thick Mesozoic sedimentary sequence deposited in the Wrangell Mountains basin. Lowermost MacColl Ridge strata conformably overlie Cretaceous strata that in turn unconformably overlie Paleozoic-Mesozoic rocks of the Wrangellia terrane (Fig. 1B). The MacColl Ridge Formation consists of 1150 m of generally upward-fining sequences of conglomerates, lithic arkosic sandstones, and mudstones deposited by a northward-prograding (present coordinates) submarine fan system within the Wrangell Mountains forearc basin (Trop et al., 1999). Uppermost strata include 10–100-cm-thick vitric tuffs and volcanoclastic sandstones. Palynologic studies of mudstones in combination with $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric dates from two interbedded tuff samples of the MacColl Ridge Formation (79.4 ± 0.7 Ma, 77.9 ± 2.1 Ma) indicate a middle to late Campanian age (Trop et al., 1999).

Strata of the MacColl Ridge Formation are exposed in an upright syncline along the modern Chitina River (Fig. 1B). Paleomagnetic samples were collected from 21 sites on both limbs of the fold (Fig. 1B). Three different lithologies, vitric tuffs, volcanoclastic sandstones, and lithic arkosic sandstones, were targeted. Samples were collected from the uppermost 750 m of the section (Fig. 1C), in contrast to Panuska (1985), who sampled only lithic arkosic sandstones and siltstones from the lowermost 30 m (Fig. 1, B and C).

PALEOMAGNETIC RESULTS

Paleomagnetic methods, data, and details of the results are given in Appendix A¹. Thermal demagnetization of vitric tuff samples produced the best paleomagnetic results (Fig. A; see footnote 1). After unblocking of a viscous present-day overprint by demagnetization temperatures to 350 °C, stable characteristic remanent magnetization (ChRM) directions were removed. Maximum unblocking temperatures reached 570 °C, suggesting magnetite as the dominant carrier of the ChRM. Many of the volcanoclastic sandstone samples also produced well-behaved and stable ChRM. In contrast, all lithic arkosic sandstone samples produced noisy and poorly defined demagnetization trajectories, often characterized by remagnetization circles (Fig. A; see footnote 1). The alternating field (AF) demagnetization produced erratic demagnetization behavior and possible growth of a rotation remanent magnetization antipodal to the first removed component, an observation also noted in the AF demagnetization of Panuska (1985).

Stable site mean directions were obtained for 15 of the 21 sites (73% of all samples; 86% of the tuff and volcanoclastic sandstone samples). Demagnetization of samples from sites 3, 6, 9, and 21 did not produce stable ChRM directions. Only a few samples from sites 2 and 16 produced ChRM directions, but because of the small sample size and large α_{95} values, these sites were also excluded from calculation of the formation mean. None of the lithic arkosic sandstone sites produced coherent ChRM site mean directions. Of the 15 sites with reliable ChRM directions, all site mean directions have east to south declinations and moderate to steeply up inclinations (Fig. 2A). The site mean directions cluster better in tilt-corrected coordinates (Fig. 2B). The McElhinny (1964) fold test is positive (i.e., acquisition of magnetization penecontemporaneous with deposition) at the 90% confidence level but statistically inconclusive at the 95% confidence level (Fig. 2C). The precision parameter (k) increases from 26.2 (k_1) to 47.2 (k_2) during tilt correction, reaching a peak of 50.8 at 80% unfolding. The k_2/k_1 ratio is 1.80, compared to the critical ratios of 1.88 (95%) and 1.64 (90%). In contrast, the McFadden and Jones (1981) fold test is positive at the 95% confidence level. The hypothesis of a common true mean direction is rejected in the in situ coordinates ($f = 4.99$) and accepted in tilt-corrected coordinates ($f = 1.58$) (number of sites [N] = 15, number of limbs

¹GSA Data Repository item 2001105, Appendix A, Methods and results, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

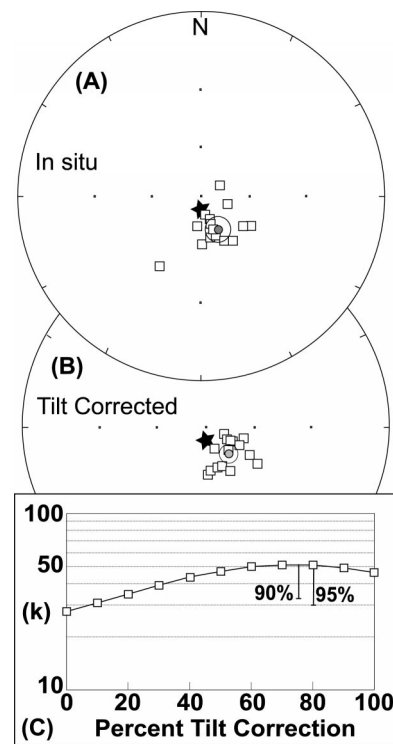


Figure 2. Equal-angle projections in (A) in situ and (B) tilt-corrected coordinates showing site mean directions (squares), formation mean direction (small gray circles), and associated 95% confidence area (larger circles). Star is expected 80 Ma reference direction based on reference pole of Dickinson and Butler (1998). (C) Incremental fold test showing variation in precision parameter (k) as function of percent tilt correction. Statistical significance of relative change in k can be evaluated against 95% and 90% confidence intervals, shown as solid black bars on curve.

[m] = 6, critical value of the F distribution at 95% significance level = 3.94).

PALEOLATITUDE

Several lines of evidence indicate that the ChRM in the MacColl Ridge Formation was acquired during deposition and that secular variation has been averaged. (1) The directions cluster better in tilt-corrected coordinates. (2) The samples are not thermally or geochemically altered. Mudstone samples contain palynomorphs and spores with Batten's thermal alteration scale values of 2 and 3 (Batten, 1996), implying a maximum post-depositional paleotemperature of 80 °C. (A.R. Sweet, 2000, personal commun.). (3) Campanian radiometric and biostratigraphic ages (Trop et al., 1999) place deposition of the upper MacColl Ridge Formation during reversed chron C33r (Cande and Kent, 1992), consistent with the reversed-polarity ChRMs. (4) The ~750 m of sampled section constitutes deposition over several million years or more.

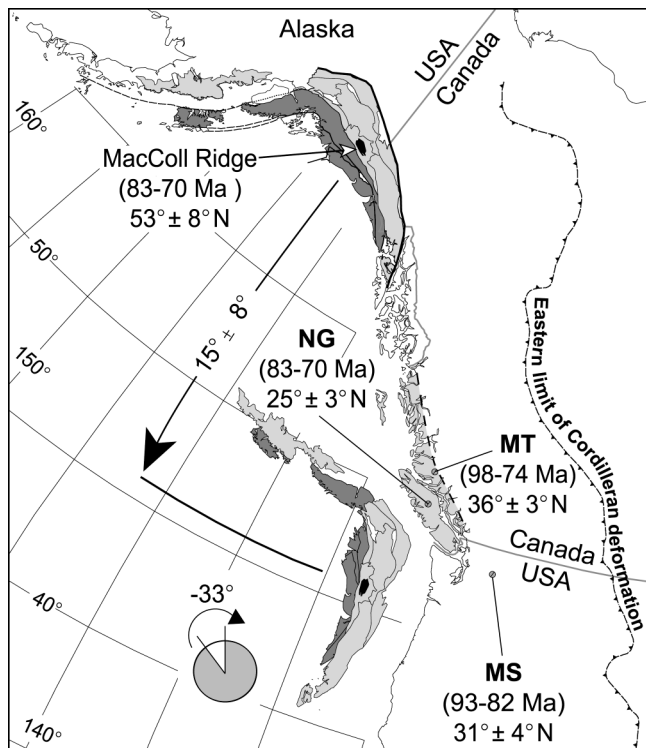


Figure 3. Map of western North America showing present-day and restored positions of Wrangellia composite terrane. Restored position shows correction for 15° of latitudinal displacement and 33° of counterclockwise rotation. Also shown are locations of other Late Cretaceous results discussed in text; MS is Mount Stuart, MT is Mount Tatlow, and NG is Nanaimo Group. Published ranges of magnetization ages and paleolatitude are given for each location.

The indication from the fold tests that the magnetization may be synfolding (and thus secondary) does not alter our overall conclusions. Bedding dips progressively decrease upsection toward the center of the syncline, indicating that folding about a nearly horizontal axis coincided with deposition, an observation consistent with the interpreted tectonic evolution of the forearc basin (Trop et al., 1999). Thus, if the ChRM was acquired during folding, it is still late Campanian in age.

Given these lines of evidence, the mean direction (declination = 140°, inclination = -69°, $\alpha_{95} = 6^\circ$), with its corresponding paleopole (lat = 68°N, long = 126°E, $A_{95} = 9^\circ$), is a representative measurement of the Late Cretaceous paleopole for the Wrangellia composite terrane. Comparison of the revised MacColl Ridge Formation pole with the Late Cretaceous reference pole (82°N, 202°E, $A_{95} = 5^\circ$) of Dickinson and Butler (1998), including error procedures of Demarest (1983), indicates $15^\circ \pm 8^\circ$ (1650 ± 890 km) of northward latitudinal displacement and $33^\circ \pm 17^\circ$ of counterclockwise rotation. These results place Wrangellia at moderate paleolatitude ($53^\circ \pm 8^\circ$ N) in the Late Cretaceous (Fig. 3). This revised paleolatitude for Wrangellia is consistent with palynoflora data, which show affinities with cratonic North American floras of the western Canadian foreland basin as opposed to those floras found farther south (Trop et al., 1999).

The revised paleolatitude ($53^\circ \pm 8^\circ$ N) is substantially more northerly than the previously reported paleolatitude ($32^\circ \pm 9^\circ$ N) of Panuska (1985). We attribute this discrepancy

to the unreliable paleomagnetic signature and limited demagnetization of the sandstones analyzed in the Panuska (1985) study. The alternative interpretation of large-scale northward transport during deposition is unrealistic. The entire 1100 m of MacColl Ridge Formation strata were deposited over an interval of 5 m.y. or less (Trop et al., 1999). The 21° (2300 km) difference in paleolatitude derived from the lower 30 m (Panuska, 1985) and upper 750 m (this study) of the MacColl Ridge Formation over 5 m.y. corresponds to a plate velocity of more than 45 cm/yr, faster than any known modern or ancient plate motion.

ROTATION

In addition to more northerly paleolatitudes, the $33^\circ \pm 17^\circ$ of counterclockwise rotation indicated by our results is consistent with the magnitude and sense of rotation for the Wrangellia composite terrane inferred from North American plate geometry (Fig. 3) and from early Tertiary volcanic rocks exposed in the Talkeetna Mountains and central Alaska Range (Hillhouse et al., 1985). In contrast, the large 240° clockwise vertical-axis rotation suggested by Panuska (1985) restores the longitudinal axis of the Wrangell Mountain forearc basin (present-day axis trend is 300°) to an orientation that is nearly perpendicular to western North America (restored-basin axis trend is 60°), and it places the subduction complex (Chugach terrane) inboard of the forearc basin. The restored orientation of the forearc basin and subduction complex based on the results of Panuska (1985) is therefore difficult to reconcile with the west to east con-

vergence and subduction that characterized western North America in the Late Cretaceous (e.g., Engebretson et al., 1987).

DISPLACEMENT HISTORY

The late Mesozoic–early Cenozoic northward translation and accretion of the allochthonous Wrangellia composite terrane along the western margin of North America is an important process to the tectonic development of the Cordillera (Plafker and Berg, 1994; Cowan et al., 1997). Numerous geologic and paleomagnetic results place the Wrangellia composite terrane at low paleolatitudes ($\sim 10^\circ$ N) during the Late Triassic (ca. 220 Ma) and at or near its present position (60° – 63° N) by 55 Ma (Hillhouse and Coe, 1994; Butler et al., 1997). Results of our study show that the Wrangellia composite terrane was at moderate paleolatitudes ($53^\circ \pm 8^\circ$ N) during the Late Cretaceous (ca. 80 Ma), and thus was displaced northward $15^\circ \pm 8^\circ$ (1650 ± 890 km) during the latest Cretaceous to Eocene (80–55 Ma). Northward translation was most likely accomplished by cumulative displacement along coast-parallel dextral strike-slip faults (Plafker and Berg, 1994). Using the preceding limitations, the minimum average displacement rate for the Wrangellia composite terrane from 80 to 55 Ma was 7 cm/yr (1650 km over 25 m.y.). The 7 cm/yr rate is a minimum because latitudinal displacements record only the northward component of terrane motion and because displacement is assumed to take place throughout the 25 m.y. interval between 80 and 55 Ma. The 7 cm/yr rate is, however, consistent with plate interaction models (e.g., Debiche et al., 1987) that suggest coast-parallel rates from 9 to 11 cm/yr, assuming 100% coupling between the ocean plates and North America (Harbert, 1990).

Our results appear incompatible with paleomagnetic results from other Late Cretaceous units in the Cordillera (Fig. 3); i.e., the 98–74 Ma Mount Tatlow strata (Wynne et al., 1995) and the 93–82 Ma Mount Stuart batholith (Beck et al., 1981; Ague and Brandon, 1996) of the Coast Plutonic Complex, and the 83–70 Ma Nanaimo Group sedimentary strata of the fragment of Wrangellia exposed on Vancouver Island (Ward et al., 1997). These paleomagnetic results place their associated terranes ~ 3000 km south of their present positions with respect to North America in the Late Cretaceous. If the Wrangellia composite terrane was associated with these other terrane fragments in the Late Cretaceous (e.g., Umhoefer, 1987), the similar magnetization ages and large differences in predicted northward displacements between the MacColl Ridge Formation and Mount Stuart, Mount Tatlow, and Nanaimo Group rocks would thus require intervals of anomalously rapid northward displacement in the Late Cretaceous, ~ 20 cm/yr.

A 20 cm/yr rate rivals the fastest known plate velocities (e.g., Meert et al., 1993) and does not match predicted rates based on plate motion models, even assuming 100% coupling between the ocean plates and North America.

Butler et al. (1989, 1997), among others, questioned the reliability of the Mount Tatlow and Mount Stuart results as faithful indicators of paleolatitude. In particular, Butler et al. (1989, 1997) argued that accurate structural corrections cannot be unequivocally established in these rock units, and thus the shallow inclinations and low paleolatitudes may simply be from incorrect tilt corrections. Kim and Kodama (1999) suggested that the shallow inclinations of the Nanaimo Group are an artifact of inclination error related to sediment compaction.

Until these outstanding questions about the age and reliability of these paleomagnetic studies are resolved, we propose an alternative and simpler displacement model in which the Wrangellia composite terrane remained at moderate paleolatitudes through most of the Late Cretaceous (Fig. 3) and was displaced northward to its present position in Alaska in the latest Cretaceous and early Tertiary. This simpler displacement model agrees with paleontologic data that place the Wrangellia composite terrane north of 30°N during the Middle Jurassic (Smith and Tipper, 1986; von Hillebrandt et al., 1992) and north of 50°N during the Late Jurassic to latest Cretaceous (von Hillebrandt et al., 1992; Trop et al., 1999).

CONCLUSION

Paleomagnetic analyses of vitric tuffs and volcanoclastic sandstones of the MacColl Ridge Formation show that these strata carry a stable Late Cretaceous remanent magnetization. Site mean directions are reversed, consistent with the reversed polarity of the geomagnetic field at the time of deposition. The paleomagnetic pole indicates that Wrangellia was at moderate paleolatitudes (offshore present-day British Columbia, Washington, and Oregon) and not low paleolatitudes (offshore present-day Baja California) in the Late Cretaceous (ca. 80 Ma). Displacement of the terrane from these moderate paleolatitudes to its present location in southern Alaska probably occurred along coast-parallel dextral strike-slip faults in the latest Cretaceous and earliest Tertiary.

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