# Neogene tilting of crustal panels near Wrangell, Alaska

Chris Butzer
Robert F. Butler*
George E. Gehrels
Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA
Cameron Davidson
Kristin O'Connell
Department of Geology, Carleton College, Northfield, Minnesota 55057, USA
Maria Luisa Crawford
Department of Geology, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010, USA

## ABSTRACT

**A late Oligocene–Miocene igneous complex south and west of Wrangell, Alaska, contains mafic dikes that yield a discordant paleomagnetic direction (inclination, $I = 70.4°$; declination, $D = 39.3°$; $\alpha_{95} = 4.8°$; $N = 72$ sites). Combined with local and regional geobarometric, metamorphic, and structural observations, the discordant paleomagnetic direction indicates east-side-up tilt by 16° about a tilt axis with azimuth = 8°. Neogene tilt of crustal blocks in the Insular superterrane accounts for much of the paleomagnetic discordance in Cretaceous plutons without the coastwise translation of >1000 km, as suggested by the Baja British Columbia hypothesis.**

**Keywords:** Coast orogen, southeast Alaska, paleomagnetism, Neogene crustal extension.

## INTRODUCTION

Rocks in the Coast orogen and Insular superterrane of southeast Alaska and western British Columbia constitute the world's largest exhumed Mesozoic–Cenozoic magmatic arc built on a continental margin (Fig. 1). The tectonic setting evolved through four stages: (1) a collisional orogen during accretion of the Alexander-Wrangellia terrane, (2) a convergent boundary with a magmatic arc and subduction complex, (3) a dextral-oblique transpressive and transtensional margin, and (4) the present dextral Queen Charlotte transform (Engebretson et al., 1985; Norton, 1995; Stock and Molnar, 1988; Hollister and Andronicos, 1997). The geologic consequences of changing plate motions have been recognized through mapping of structures, pluton and metamorphic barometry, and geochronology in the region between Prince Rupert and Petersburg (Crawford et al., 1987; Gehrels and Berg, 1992; McClelland and Gehrels, 1992; Cook and Crawford, 1994; Andronicos et al., 1999; Stowell and Crawford, 2000).

Discordant paleomagnetic directions from Cretaceous rocks of the northern North American Cordillera have been interpreted to indicate that the Insular superterrane, the Coast Mountains and North Cascades, and portions of interior British Columbia were located as much as 4000 km south of their present locations during mid-Cretaceous time (Irving et al., 1996). This Baja British Columbia hypothesis challenges conventional views of North American Cretaceous paleogeography because it implies the concurrent development of two magmatic arcs occupying the same position along the continental margin (Dickinson and Butler, 1998; Butler et al., 2001a). Full review of the Baja British Columbia controversy is beyond the scope of this paper (see Cowan et al., 1997; Housen and Beck, 1999; Mahoney et al., 2000; and Butler et al., 2001a). Resolution of the controversy is important to understanding the tectonics of the North American Cordillera in particular and continental margins in general.

The original motivation for the Baja British Columbia hypothesis was the observation of discordant paleomagnetic directions in Mesozoic plutonic rocks of the Insular superterrane in western British Columbia (Symons, 1977a, 1977b), the Coast Mountains of southern British Columbia (Irving et al., 1985), and the North Cascades (Beck et al., 1981). On the assumption that present horizontal approximates paleohorizontal, discordant paleomagnetic directions in Cretaceous plutons have been interpreted to indicate as much as 4000 km of post-mid-Cretaceous northward transport along the continental margin. Alternatively, these discordant directions could be accounted for by systematic northeast-side-up tilt by ~30° during uplift. The question of whether systematic post-mid-Cretaceous tilting of crustal blocks has occurred in the Insular superterrane of western British Columbia and southeast Alaska is a central issue in the Baja British Columbia controversy.

In this paper we report geologic, geochronologic, and paleomagnetic data from mafic dikes of late Oligocene–early Miocene age that are widespread south and west of Wrangell, Alaska. These observations document tilting of crustal panels during Neogene extension of the continental margin in this area. Paleomagnetic directions obtained from mafic dikes in the Queen Charlotte Islands by Irving et al. (1992) indicate a similar history of crustal tilt.

## GEOLOGIC SETTING

Essential elements of the geologic development of the continental margin near Wrangell are as follows: (1) Mesozoic plutonism culminated in the mid-Cretaceous (115–89 Ma) with plutons emplaced during an episode of shortening orthogonal to the NW strike of the orogen (Crawford et al., 1987). (2) Pluton emplacement between ca. 70 and 53 Ma was accompanied by a change from shortening to arc-parallel and arc-oblique displacement (Klepeis and Crawford, 1999; Crawford et al., 1999). (3) Emplacement, cooling, and uplift histories of late Mesozoic and Cenozoic plutons have documented east-side-up tilting of crustal blocks during formation of the vertical Coast shear zone ca. 50 Ma (Cook and Crawford, 1994; Klepeis and Crawford, 1999; Butler et al., 2001b). (4) Extension occurred across the region in the late

---

*Present address: Department of Chemistry and Physics, University of Portland, 5000 North Willamette Boulevard, Portland, Oregon 97203, USA.

*Geology;* December 2004; v. 32; no. 12; p. 1061–1064; doi: 10.1130/G20855.1; 3 figures; Data Repository item 2004167.

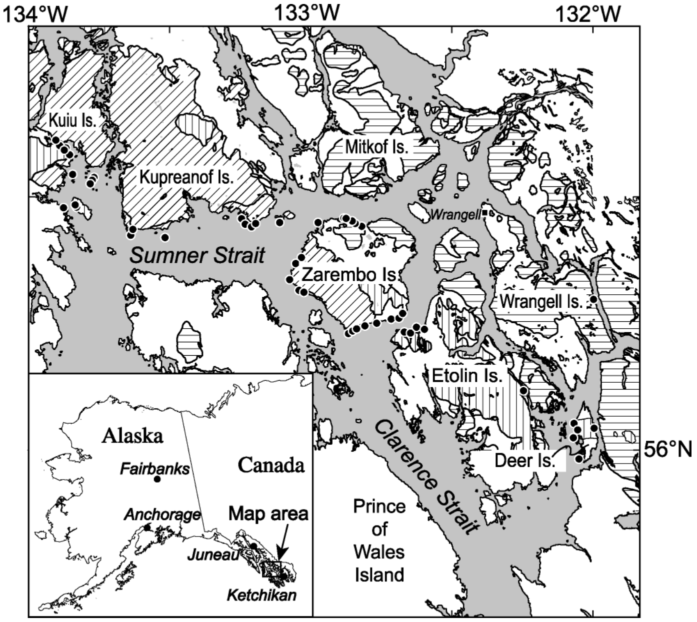

**Figure 1. Geologic map and paleomagnetic sampling site locations (dots). Patterns: horizontal lines—Cretaceous plutonic rocks; vertical lines—Tertiary plutonic rocks; diagonal lines—Tertiary volcanic rocks. Inset map shows location of map within northwest North America.**

Tertiary, accommodated by N- and NW-trending normal faults (Rohr and Dietrich, 1992; Evenchick et al., 1999; Davidson et al., 2003). (5) Structural geologic, fission-track, and (U-Th)/He dating studies in Douglas Channel by Parrish (1983) and Farley et al. (2001) document an increased exhumation rate of the Coast Mountains during the past 4 m.y.

The region near Wrangell, Alaska, contains plutons emplaced at intermediate (>15 km) to shallow (<5 km) crustal levels at various times during the past 100 m.y. (Fig. 1). South and west of Wrangell, Cretaceous (93–89 Ma) plutons show ~500 MPa (5 kbar) maximum pressure of emplacement as demonstrated by andalusite in the contact aureoles. The youngest of these plutons (90 Ma) record crustal thickening during emplacement, as shown by kyanite- and sillimanite-bearing assemblages that indicate pressures of >600 MPa. Cook and Crawford (1994) and Himmelberg et al. (2004) showed that kyanite replaces andalusite in some of these aureoles and suggested that some of these plutons were rapidly buried shortly after intrusion owing to mid-Cretaceous top-to-the-west thrusting, as observed in the Prince Rupert area (Crawford et al., 1987). A major 30–15 Ma igneous complex is exposed in a northwest-trending zone from Etolin Island to Kuiu Island (Karl et al., 1999; Lindline et al., 2000, 2004). Post–15 Ma east-side-up tilting is suggested by plutonic rocks at the southeast end of the complex that could represent a magma chamber for the coeval volcanic complex to the northwest (Lindline et al., 2004). On Deer Island, the plutonic rocks of the Kuiu-Etolin igneous complex have imparted a low-pressure, high-temperature cordierite-bearing thermal aureole on the country rocks. Geobarometers suggest early Miocene pluton emplacement at ~350 MPa (equivalent to ~10 km depth). The volcanic complex, composed of basaltic and rhyolitic flows, appears to have been fed by steeply dipping 0.5–5-m-thick mafic and felsic dikes that crosscut all rock types and earlier-formed structures across the area and the volcanic pile.

## ISOTOPIC AGE DETERMINATIONS

Two whole-rock mafic dike samples, extracted from paleomagnetic cores at site WT277 from Zarembo Island and WT305 from Wrangell Island, were degassed by using a conventional furnace at the University of Wisconsin Rare Gas Geochronology Laboratory. Singer and Brown (2002) detailed the analytical procedures and data-reduction methods used in this study. Argon-release spectra are illustrated in Data Repository Figure DR1.[1] Sample WT277 yielded a weighted-mean plateau age of 14.7 ± 1.0 Ma, and sample WT305 yielded a weighted-mean plateau age of 30.1 ± 0.2 Ma. Inverse isochrons for these samples yield similar dates with $^{40}$Ar/$^{36}$Ar intercepts indistinguishable from atmosphere (Fig. DR1; see footnote 1). These dates agree with K-Ar biotite dates reported by Brew et al. (1984) from shallow-level plutonic rocks on Kupreanof, Zarembo, and Etolin Islands (ca. 20 Ma) and rhyolite dikes (15 Ma) in the Coast Mountains east of the study area. We interpret these dates as conservative estimates of the time lapsed since the solidification of the dikes. Many of the dikes cut volcanic and plutonic rocks assigned to the Kuiu-Etolin igneous belt. Plutonic members of this belt have been dated by K/Ar methods on hornblende and biotite (Douglass et al., 1989) and by whole-rock Rb/Sr and fission-track methods (Lindline et al., 2000). These ages range from 25.6 to 17.3 Ma. The concordance of all the ages, despite markedly different closure temperatures, suggests rapid cooling for the plutonic part of the complex.

## PALEOMAGNETIC METHODS AND RESULTS

Paleomagnetic samples were collected from basaltic dikes exposed on shorelines of islands west and south of Wrangell in southeastern Alaska (Fig. 1). Eight or more oriented core samples were collected from each dike. Details of the paleomagnetic analyses are provided in Appendix DR1 (see footnote 1). The resulting 72 site-mean directions are listed in Table DR1 (see footnote 1) and are equally divided between normal and reversed polarities (Fig. 2A). The overall mean paleomagnetic direction is inclination, $I = 70.4^\circ$, declination, $D = 39.3^\circ$, $\alpha_{95} = 4.8^\circ$ (Fig. 2B), whereas the expected Oligocene direction is $I = 73.3^\circ \pm 2.5^\circ$, $D = 350.0^\circ \pm 7.8^\circ$ (using reference pole of Diehl et al., 1988). Comparison of the observed and expected directions yields inclination flattening ($F \pm \Delta F$) of $2.9^\circ \pm 4.3^\circ$ and rotation of declination ($D \pm \Delta D$) of $49.3^\circ \pm 13.1^\circ$. The concordant paleomagnetic inclination and discordant declination could indicate either (1) $49.3^\circ \pm 13.1^\circ$ clockwise vertical-axis rotation or (2) east-side-up tilt by 16° with azimuth of tilt axis = 8° (Fig. 2B).

## EVIDENCE FOR CRUSTAL TILT

Most geologic terrane boundaries and Paleozoic to Cenozoic structures throughout southeast Alaska trend northwest, parallel to the continental margin (Fig. 1). It is therefore unlikely that crustal blocks in this region have undergone the ~50° clockwise vertical-axis rotation required to explain the observed paleomagnetic direction. On the other hand, the east-side-up tilt interpretation of the discordant paleomagnetic direction is supported by a variety of geologic observations.

The late Oligocene–early Miocene dikes fall into two groups: one set striking north-northwest and the other set striking northeast. The average pole to these dikes plunges 16° toward 287°, showing that the average dike orientation dips 74° toward 107° (Fig. 2C). Removing the east-side-up tilt of 16° about a horizontal axis with azimuth of 8° (as indicated by the tilt interpretation of the paleomagnetic results) results in a vertical dike orientation with the average pole horizontal (Fig. 2D). These observations suggest that the late Oligocene–early Miocene dikes were intruded with a vertical orientation during extension of the

---

[1] GSA Data Repository item 2004167, Figure DR1, argon analyses diagrams, Appendix DR1, paleomagnetic analyses, Figure DR2, vector-component diagram, and Table DR1, site-mean directions of characteristic magnetization, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

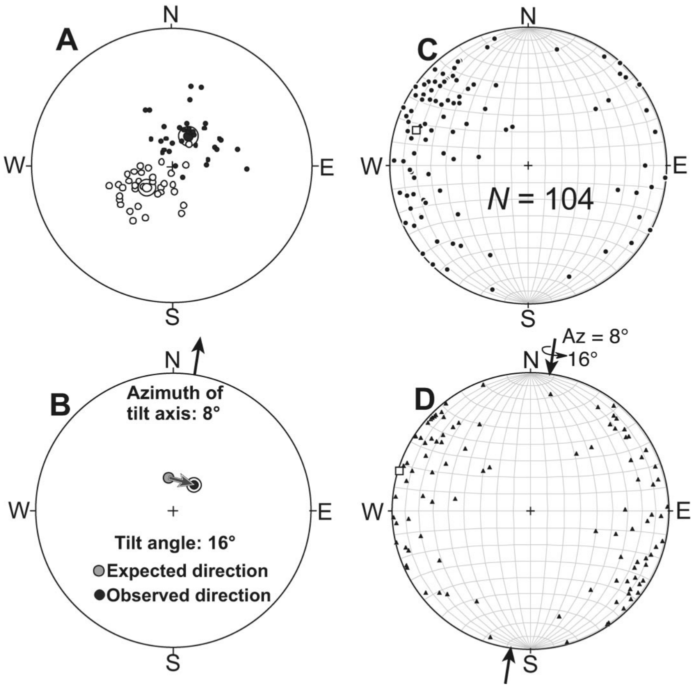

**Figure 2. Equal-area projections of paleomagnetic directions and dike orientations. A: Site-mean paleomagnetic directions. Filled circles are in lower hemisphere; open circles are in upper hemisphere. Mean of normal (reversed) polarity sites is illustrated with larger filled (open) circle surrounded by 95% confidence limits. B: Mean observed direction is shown by filled circle surrounded by 95% confidence limits. Expected direction is indicated by gray circle. Arrow indicates deflection of expected direction to observed mean direction by 16° east-side-up tilt about horizontal axis with azimuth of 8°. C: Mafic dike orientations. Lower-hemisphere projection of poles to dikes (dots) and mean pole (open square) with trend = 287° and plunge = 16°. D: Projection of poles to dikes (triangles) and mean orientation (open square with trend = 287° and plunge = 00°) after correction for tilt are indicated by paleomagnetic directions.**

continental margin inboard of the Queen Charlotte transform fault. East-side-up tilting of crustal blocks east of the Queen Charlotte fault is also supported by seismic data, collected by Rohr et al. (2000), that show Miocene marine sediments deposited on the Insular superterrane in Dixon Entrance dip as much as 20° to the west.

Regional geologic evidence indicates that east-side-up tilt of crustal panels has affected large areas of the continental margin from southern Prince of Wales Island north at least to the latitude of Wrangell, Alaska. The late Oligocene–early Miocene Etolin-Kuiu igneous complex (Fig. 1) comprises shallow-level volcanic rocks on the northwest and plutons intruded at ∼10 km depth on the southeast (Lindline et al., 2000, 2004). The east-west dimension of the igneous complex is ∼80 km. If the ∼10 km structural relief across this belt resulted from coherent tilt about a horizontal axis with azimuth of 8°, the required tilt angle is 8° or half of the required 16° Neogene tilt indicated by the paleomagnetic and structural geologic observations from the mafic dikes. Paleozoic rocks of the Alexander terrane on Prince of Wales Island have very low metamorphic grade at the northwest corner of the island. Metamorphic grade increases toward the southeast, implying ∼10 km of structural relief from northwest to southeast across the island with east-west dimension ∼80 km (Gehrels and Berg, 1992). The assumption that this gradient in metamorphic grade resulted from east-side-up tilt of the entire island also implies a tilt angle of ∼8° or half of the 16° Neogene tilt herein documented for areas east of Prince of Wales Island.

The observations above suggest that ∼8° of the 16° Neogene tilt could have resulted from coherent tilt of the 60–100-km-wide crustal panel containing the late Oligocene–early Miocene igneous complex (Fig. 3A). This leads to the proposal that the remaining 8° of tilt was accommodated by smaller crustal panels (Fig. 3B). These smaller blocks could be represented by individual islands, each of ∼20 km dimension, with intervening ocean canals and passages underlain by normal faults and accommodation zones as inferred for the Portland Canal area near Prince Rupert, British Columbia (Butler et al., 2001b). Because rock exposures are almost entirely limited to shorelines and exposed rocks are dominantly igneous rocks within which faults are difficult to recognize, even smaller blocks may be involved in and contribute to the tilting.

## CONCLUSIONS

There is growing evidence that systematic northeast- or east-side-up tilts have affected widely distributed parts of the continental margin of western North America. Barometry of the metamorphic aureole surrounding the Spuzzum pluton in the southern Coast Mountains indicates northeast-side-up tilt by 33° (Brown and Burmester, 1991). Rohr and Dietrich (1992) documented that Miocene marine strata of the Feeney basin south of Prince Rupert dip 15°–20° to the southwest. The Paleocene–Eocene Quottoon plutonic complex in the Portland Inlet region north of Prince Rupert yields paleomagnetic directions indicating local northeast-side-up tilt by as much as 40° during Eocene extension of the Coast Mountains (Butler et al., 2001b). Pressures obtained on the contact-metamorphic aureole of the 90 Ma Bell Island pluton exposed between Ketchikan and Wrangell, Alaska, document that this pluton tilted southeast-side-up by 14° between 55 and 50 Ma (Cook and Crawford, 1994). The evidence presented here demonstrates that east-side-up tilt of ∼16° affected the region south and west of Wrangell during the Neogene. It is thus abundantly clear that northeast- or east-side-up tilting is widespread within the continental margin of British Columbia and southeast Alaska. Crustal tilt accounts for a large part of the paleomagnetic discordance in Cretaceous plutons of this region,

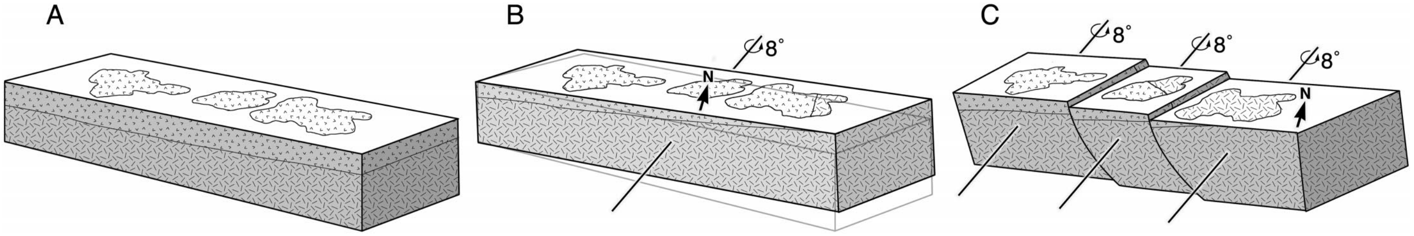

**Figure 3. Model of tilting crustal panels. V pattern indicates volcanic and shallow-level intrusive rocks. Jackstraw pattern indicates plutonic rocks intruded at ~10 km or deeper levels within crust. A: Original configuration of late Oligocene–early Miocene igneous complex extending from Etolin Island to Kuiu Island. B: Result of ~8° coherent east-side-up tilt of entire igneous complex. C: Result of superimposed ~8° tilt of smaller crustal blocks perhaps represented by individual islands.**

and the original basis for the Baja British Columbia hypothesis is accordingly diminished.

## ACKNOWLEDGMENTS

This research was funded by grants EAR-0207615, EAR-0207586, and EAR-0234003 from the Tectonics Program of the National Science Foundation and the Charles W. Potts Endowment Fund for Student/Faculty Research at Carleton College. L. Murray, Y. Lewis, D. Ohman, B. Singer, and X. Zhang provided laboratory assistance. We thank R. Matthews, F. Churchill, L. Fabrello, E. Lucas, and T. Lucas for logistical support during field work. J. Geissman and L. Brown improved the manuscript through careful reviews.

## REFERENCES CITED

Andronicos, C., Hollister, L.S., Davidson, C., and Chardon, D., 1999, Kinematics and tectonic significance of transpressive structures within the Coast Plutonic Complex, British Columbia: Journal of Structural Geology, v. 21, p. 229–243.

Beck, M.E., Jr., Burmester, R.F., and Schoonover, R., 1981, Paleomagnetism and tectonics of Cretaceous Mt. Stuart batholith of Washington: Translation or tilt?: Earth and Planetary Science Letters, v. 56, p. 336–342.

Brew, D.A., Ovenshine, A.T., Karl, S.M., and Hunt, S.J., 1984, Preliminary reconnaissance geologic map of the Petersburg and parts of the Port Alexander and Sumdum quadrangles, southeastern Alaska: U.S. Geological Survey Open-File Report 84-405, 43 p., scale 1:250,000.

Brown, E.H., and Burmester, R.F., 1991, Metamorphic evidence for tilt of the Spuzzum pluton: Diminished basis for the ‘‘Baja British Columbia’’ concept: Tectonics, v. 10, p. 978–985.

Butler, R.F., Gehrels, G.E., and Kodama, K.P., 2001a, A moderate translation alternative to the Baja British Columbia hypothesis: GSA Today, v. 11, no. 6, p. 4–10.

Butler, R.F., Gehrels, G.E., Crawford, M.L., and Crawford, W.A., 2001b, Paleomagnetism of the Quottoon plutonic complex in the Coast Mountains of British Columbia and southeastern Alaska: Evidence for tilting during uplift: Canadian Journal of Earth Sciences, v. 38, p. 1367–1384.

Cook, R.D., and Crawford, M.L., 1994, Exhumation and tilting of the western metamorphic belt of the Coast orogen in southern southeastern Alaska: Tectonics, v. 13, p. 528–537.

Cowan, D.S., Brandon, M.T., and Garver, J.L., 1997, Geologic tests of hypotheses for large coastwise displacements—A critique illustrated by the Baja British Columbia controversy: American Journal of Science, v. 297, p. 117–173.

Crawford, M.L., Hollister, L.S., and Woodsworth, G.J., 1987, Crustal deformation and regional metamorphism across a terrane boundary, Coast Plutonic Complex, British Columbia: Tectonics, v. 6, p. 343–361.

Crawford, M.L., Klepeis, K.A., Gehrels, G., and Isachsen, C., 1999, Batholith emplacement at mid-crustal levels and its exhumation within an obliquely convergent margin: Tectonophysics, v. 312, p. 57–78.

Davidson, C., Davis, K.J., Bailey, C.M., Tape, C.H., Singleton, J., and Singer, B., 2003, Age, origin, and significance of brittle faulting and pseudotachylyte along the Coast shear zone, Prince Rupert, British Columbia: Geology, v. 31, p. 43–46.

Dickinson, W.R., and Butler, R.F., 1998, Coastal and Baja California paleomagnetism reconsidered: Geological Society of America Bulletin, v. 110, p. 1268–1280.

Diehl, J.F., McClannahan, K.M., and Bornhorst, T.J., 1988, Paleomagnetic results from the Mogollon-Datil volcanic field, southwestern New Mexico, and a refined mid-Tertiary reference pole for North America: Journal of Geophysical Research, v. 93, p. 4869–4879.

Douglass, S.L., Webster, J.H., Burrell, P.D., Lanphere, M.L., and Brew, D.A., 1989, Major-element chemistry, radiometric ages, and locations of samples from the Petersburg and parts of the Port Alexander and Sumdum quadrangles, southeastern Alaska: U.S. Geological Survey Open-File Report 89-527, 64 p.

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

Evenchick, C.A., Crawford, M.L., McNicoll, V.J., Currie, L.D., and O'Sullivan, P.B., 1999, Early Miocene or younger normal faults and other Tertiary structures in west Nass River map area, northwest British Columbia, and adjacent parts of Alaska: Geological Survey of Canada Current Research 1999-A, p. 1–11.

Farley, K.A., Rusmore, M.E., and Bogue, S.W., 2001, Post–10 Ma uplift and exhumation of the northern Coast Mountains, British Columbia: Geology, v. 29, p. 99–102.

Gehrels, G.E., and Berg, H.C., 1992, Geologic map of southeastern Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1867, scale 1:600,000.

Himmelberg, G.R., Haeussler, P.J., and Brew, D.A., 2004, Emplacement, rapid burial, and exhumation of 90-Ma plutons in southeastern Alaska: Canadian Journal of Earth Sciences, v. 41, p. 87–102.

Hollister, L.S., and Andronicos, C.L., 1997, A candidate for the Baja British Columbia fault system in the Coast Plutonic Complex: GSA Today, v. 7, no. 11, p. 1–7.

Housen, B.A., and Beck, M.E., Jr., 1999, Testing terrane transport: An inclusive approach to the Baja B.C. controversy: Geology, v. 27, p. 1143–1146.

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

Irving, E., Souther, J.G., and Baker, J., 1992, Tertiary extension and tilting in the Queen Charlotte Islands: Evidence from dyke swarms and their paleomagnetism: Canadian Journal of Earth Sciences, v. 29, p. 1878–1898.

Irving, E., Wynne, P.J., Thorkelson, D.J., and Schiarizza, P., 1996, Large (1000 to 4000 km) northward movements of tectonic domains in the northern Cordillera, 83 to 45 Ma: Journal of Geophysical Research, v. 101, p. 17,901–17,916.

Karl, S.M., Haeussler, P.J., and McCafferty, A., 1999, Reconnaissance geologic map of the Duncan Canal–Zarembo Island area, southeastern Alaska: U.S. Geological Survey Open-File Report 99-168, 30 p.

Klepeis, K.A., and Crawford, M.L., 1999, High-temperature arc-parallel normal faulting and transtension at the roots of an obliquely convergent orogen: Geology, v. 27, p. 7–10.

Lindline, J., Crawford, W.A., Crawford, M.L., and Omar, G.I., 2000, Post-accretion magmatism within the Kuiu-Etolin igneous belt, southeastern Alaska: Canadian Mineralogist, v. 38, p. 951–974.

Lindline, J., Crawford, W.A., and Crawford, M.L., 2004, A bimodal volcanic-plutonic system: The Zarembo Island extrusive suite and the Burnett Inlet intrusive complex: Canadian Journal of Earth Sciences, v. 41, p. 355–375.

Mahoney, J.B., Tikoff, B., Maxson, J., and Haugerud, R.A., 2000, Terrane accretion along the western cordilleran margin: Constraints on timing and displacement: GSA Today, v. 10, p. 11–13.

McClelland, W.C., and Gehrels, G.E., 1992, Upper Jurassic–Lower Cretaceous basinal strata along the Cordilleran margin: Implications for the accretionary history of the Alexander-Wrangellia-Peninsular terrane: Tectonics, v. 11, p. 823–835.

Norton, I.O., 1995, Plate motions in the North Pacific: The 43 Ma nonevent: Tectonics, v. 14, p. 1080–1094.

Parrish, R.R., 1983, Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia: 1. Fission track dating, apparent uplift rates, and patterns of uplift: Tectonics, v. 2, p. 601–631.

Rohr, K.M.M., and Dietrich, J.R., 1992, Strike-slip tectonics and development of the Tertiary Queen Charlotte Basin, offshore western Canada: Evidence from seismic reflection data: Basin Research, v. 4, p. 1–19.

Rohr, K.M.M., Scheidhauer, M., and Trehu, A.M., 2000, Transpression between two warm mafic plates: The Queen Charlotte fault revisited: Journal of Geophysical Research, v. 105, p. 8147–8172.

Singer, B., and Brown, L.L., 2002, The Santa Rosa event: $^{40}$Ar/$^{39}$Ar and paleomagnetic results from the Valles Rhyolite near Jaramillo Creek, Jemez Mountains, New Mexico: Earth and Planetary Science Letters, v. 197, p. 51–65.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of the North American relative to the Farallon, Kula and Pacific plates: Tectonics, v. 7, p. 1339–1384.

Stowell, H.H., and Crawford, M.L., 2000, Metamorphic history of the Coast Mountains orogen, western British Columbia and southeastern Alaska, *in* Stowell, H.H., ed., Tectonics of the Coast Mountains, southeastern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 257–283.

Symons, D.T.A., 1977a, Geotectonics of Cretaceous and Eocene plutons in British Columbia: A paleomagnetic fold test: Canadian Journal of Earth Sciences, v. 14, p. 1246–1262.

Symons, D.T.A., 1977b, Paleomagnetism of Mesozoic plutons in the westernmost Coast Complex of British Columbia: Canadian Journal of Earth Sciences, v. 14, p. 2127–2139.

Manuscript received 2 June 2004
Revised manuscript received 31 August 2004
Manuscript accepted 2 September 2004

Printed in USA