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Notes

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ABSTRACT

During mid- to Late Cretaceous time, the northern paleo–Pacific Ocean was characterized by subduction for >6000 km along strike. The associated magmatic and orogenic belt now comprises parts of the U.S. and Canadian Cordillera, Alaska, and the Russian Far East. Crustal shortening in the northwestern Cordillera sector of the belt was contemporaneous with extension in northern and interior Alaska and the Bering Strait region, while extensional to neutral tectonics prevailed in the Sea of Okhotsk region, Russian Far East. The along-strike continuity of magmatism during the ~120–80 Ma time interval resulted from subduction beneath the northern circum-Pacific margin, even beneath the broadest parts of the belt in the Alaska and Bering Strait region, which we suggest were modified by large-magnitude crustal extension. Variations in deformational style along strike of the orogenic belt may be related to changes in the nature of the mechanical coupling between the subducting oceanic and overriding continental plates, where the central extensional part of the belt developed above a part of the slab characterized by southward retreat or rollback of the subduction zone.

INTRODUCTION

Currently popular tectonic models ascribe growth of the northern circum-Pacific continental margin to accretion and collision of allochthonous crustal fragments, modified by orogen-parallel strike-slip faulting (e.g., Coney et al., 1980; Oldow et al., 1989). Here we evaluate these models for the northern circum-Pacific continental margin during the mid- to Late Cretaceous (~120–80 Ma), a time of unusually voluminous subduction-related magmatism. Although magmatism in this belt was earlier in places and in general continued into the Tertiary, we focus specifically on the mid- to Late Cretaceous part of this history. Magmatism and deformation along strike of the continental margin during this time span indicate major differences in tectonic styles (Fig. 1). For example, mid- to Late Cretaceous intra-arc shortening in the Cordillera from the latitude of northern Washington to southeast Alaska (Rubin et al., 1990) changes farther north to large-magnitude crustal extension in the Alaskan and Bering Strait sector of the belt (Dumitru et al., 1995; Miller and Hudson, 1991; Pavlis et al., 1993), indicating that parts of the orogenic belt were shaped by extensional rather than contractional tectonics. These differences in tectonic style invite reappraisal of kinematic models for Cretaceous deformation along the northern paleo-Pacific margin and suggest that changes in mechanical coupling between the subducting and overriding plates along the margin were the first-order influence on orogenesis, not the collision of allochthonous terranes.

CANADIAN AND SOUTHEAST ALASKA SECTOR

Geologic field studies in northern Washington, western British Columbia, and southeast Alaska indicate that west-vergent thrust faulting was active from about 100 to 85 Ma and involved both crystalline basement and supracrustal rocks. In southeast Alaska (Rubin et al., 1990; Gehrels et al., 1992; McClelland et al., 1992; Rubin and Saleeby, 1992) and near Prince Rupert, British Columbia (Crawford et al., 1987), the thrust belt is localized along the eastern edge of the Alexander terrane and consists of an imbricate series of west-vergent thrust sheets (Fig. 1). The thrust belt extends to the San Juan Islands and northwest Cascades (Brandon et al., 1988; McGroder, 1989). Although contractional deformation and regional metamorphism in the orogenic belt are complex and vary in detail along a 1500 km strike length (Fig. 1), the similarities in structural style and timing of deformation are remarkable. Coeval east-vergent thrusting and folding occurred along this sector of the orogen far inboard of the continental margin (Evenchick, 1991; Rusmore and Woodsworth, 1988; McGroder, 1989) (Fig. 1).

Mid- to Late Cretaceous thrust faulting and folding were broadly coeval with arc magmatism (Crawford and Crawford, 1991). Subduction-related Cretaceous calc-alkalic intrusive rocks form a relatively narrow belt along the eastern margin of the Wrangellian and Alexander terranes (Arth et al., 1988; Rubin et al., 1990) (Fig. 1) and were coeval with intra-arc folding and thrust faulting. In the San Juan and northern Cascades thrust system, the Mount Stuart and related 80–90

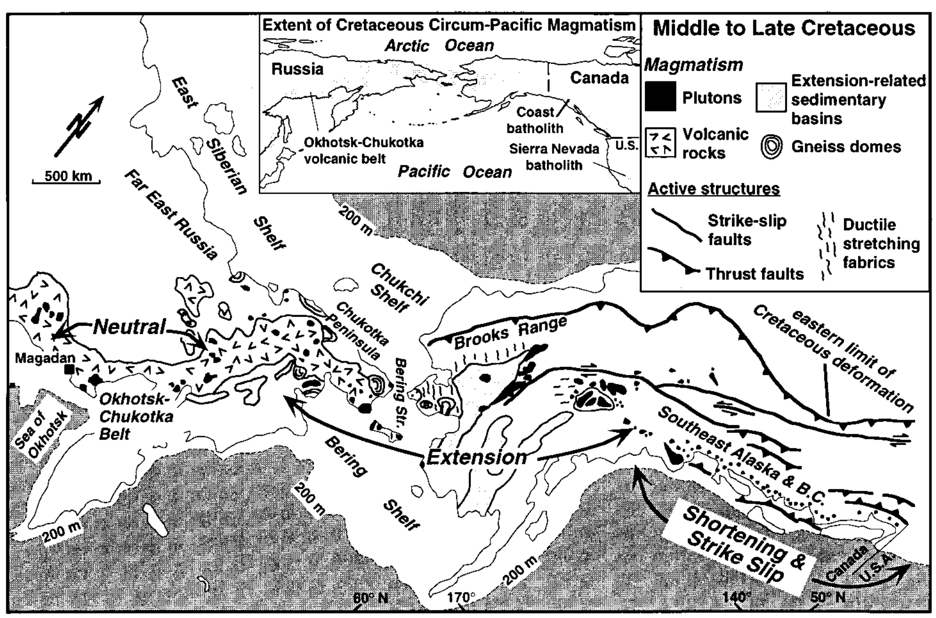

Figure 1. Generalized geologic map showing major tectonic elements in northern circum-Pacific of western Canada, southeast and northern Alaska, and Chukotka Peninsula, Russia. Inset map shows location of study area and regional extent of mid-Cretaceous volcanoplutonic belt. B.C. = British Columbia.

Ma plutons represent the latest stages of the Cretaceous arc (Walker and Brown, 1991).

In southeast Alaska, western British Columbia, and the San Juan–northern Cascades area, the youngest strata fully involved in the deformation are of Albian age. To the south, in the San Juan Island thrust system, Santonian (~84 Ma) strata of the Nanaimo Group contain clasts derived from some of the metamorphosed units in the thrust sheets and mostly postdate thrusting (Brandon et al., 1988). In the northern Cascades, east of the Straight Creek fault, U-Pb zircon geochronology on plutons and orthogneiss (Walker and Brown, 1991) coupled with structural studies (Brown, 1987; Miller, 1985; McGroder, 1989) indicate that thrust-related deformation was coeval with voluminous mid-Cretaceous magmatism. In southeast Alaska and western British Columbia, geochronologic data combined with structural studies (Crawford et al., 1987; Gehrels et al., 1992; McClelland et al., 1992; Rubin and Saleeby, 1992) indicate that thrust faulting began between Albian and early Cenomanian time and had ceased by the Turonian.

ALASKA SECTOR

In contrast to the synmagmatic contractional deformation to the south, the central and northern Alaska and western Yukon Territory sector of the orogenic belt underwent significant regional extension in the mid- to Late Cretaceous, postdating an episode of Jurassic to Early Cretaceous contraction (e.g., Miller and Hudson, 1991; Pavlis et al., 1993; Dumitru et al., 1995). Widespread exposure of high-pressure–low-temperature metamorphic rocks in northern Alaska attests to the earlier crustal-thickening event (e.g., Dusel-Bacon et al., 1989). Much of the Alaskan segment of the orogen, however, is now low lying, underlain by normal to thin continental crust (~30 km thick; Barnes, 1977; Beaudoin et al., 1992) that we attribute in part to Cretaceous extension (e.g., Miller and Hudson, 1991). Evidence for Cretaceous regional extension includes the formation of marine basins across interior Alaska, the development and exhumation of vast tracts of subhorizontally foliated and strongly lineated metamorphic tectonites, including rocks earlier metamorphosed under blueschist-facies conditions, and the apparent normal faults that bound many of the terranes of the Alaskan Cordillera (Fig. 1) (Miller and Hudson, 1991). Despite controversy over the exact timing and magnitude of this extension, existing data are compatible with the interpretation that extension occurred in the Albian and continued into the Late Cretaceous (Miller and Hudson, 1991; Pavlis et al., 1993).

A belt of mid- to Late Cretaceous plutons crosses the region of extension in Alaska and delimits the timing of events (Fig. 1). Although similar in age to the Coast Batholith of western Canada and southeast Alaska, the magmatic belt is extremely wide in Alaska and the Bering Strait region, where it is 600 km across (Fig. 1), even after restoration of younger strike-slip faults that may duplicate part or all of the belt in Alaska (Fig. 1). Plutons in central Alaska span the 120–80 Ma age range, vary considerably in composition and isotopic signature (Miller, 1989; Arth et al., 1989a, 1989b; Roeske et al., 1991), and cut numerous mapped terrane boundaries including faults inferred to be extensional (Miller and Hudson, 1991). In widely separated regions, magmatism was contemporaneous with ductile deformation associated with crustal thinning and uplift of deep-seated rocks rather than collision or shortening (e.g., Amato et al., 1994; Sisson et al., 1990; Pavlis et al., 1993). These relationships support an extensional tectonic setting for magmatism.

RUSSIAN FAR EAST SECTOR

The mid- to Late Cretaceous Okhotsk-Chukotka volcanic and plutonic belt is continuous from the Chukotka Peninsula to northeastern China, a distance of >3500 km (Fig. 1). Along most of its length, the volcanic belt is relatively narrow, except on the Chukotka Peninsula that adjoins the Bering Strait. There, the volcanic belt is wide, some volcanic sequences are tilted, and plutons are commonly associated with both volcanic sequences and deeper-level metamorphic rocks. On both sides of the Bering Strait, high-grade metamorphic rocks form a series of granite-cored, sillimanite-bearing gneiss domes (Natal'in, 1979; Miller et al., 1992; Amato et al., 1994). In Chukotka, Albian to latest Cretaceous volcanic rocks and caldera complexes represent supracrustal sequences that flank and are in places in fault contact with the granite-cored, sillimanite-bearing gneiss domes (Natal'in, 1979; Shul'diner and Nedomolkin, 1976). Along strike to the south, volcanic and sedimentary rocks of the Okhotsk-Chukotka belt lie in angular unconformity on older Mesozoic rocks (Fig. 1; Zonenshain et al., 1990). At the latitude of Magadan (Fig. 1), the volcanic succession is nearly flat lying; stocks, dikes, and hypabyssal intrusive rocks are the same age as the overlying volcanic pile and form a fairly narrow belt that is subparallel to the coastline. Granite-cored gneiss domes across the Bering Strait region probably developed in an extensional tectonic setting above a southward-retreating subduction zone in the Cretaceous (Amato, 1995).

The volcanic and associated plutonic rocks of the Okhotsk-Chukotka belt developed during a relatively short time interval that spans the Albian through Cenomanian (Belyi, 1973, 1994). Volcanic rocks are calc-alkalic and mark the location of a mid- to Late Cretaceous convergent continental margin (Zonenshain et al., 1990). On the basis of the relations described above, most of the region developed in a neutral tectonic setting, distinct from its U.S. and Canadian counterpart. The Chukotka Peninsula may have developed in an extensional setting as did adjacent Alaska.

TECTONIC SYNTHESIS

When viewed in its entirety, the temporal and spatial continuity of the Cretaceous circum-Pacific magmatic belt (Fig. 1) provides compelling evidence for continuous subduction beneath the northern circum-Pacific margin during the time spanning the mid-Cretaceous to Early Tertiary. During the restricted 120–80 Ma interval, contrasting tectonic styles developed along strike. A narrow fold-and-thrust belt, involving intra-arc volcanic rocks and continental shelf and slope strata as well as crystalline basement, developed coeval with intrusion of mid-Cretaceous plutons in northwestern Canada and southeastern Alaska. The orogenic belt in Alaska, the Bering Strait region, and the Chukotka Peninsula, Russia, is far wider and includes distributed sedimentary basins and granite-cored, sillimanite-bearing gneiss domes, which may be similar in origin to extensional core complexes of the Aegean or Basin and Range (e.g., Miller and Hudson, 1991; Pavlis et al., 1993).

During the Jurassic (~180–150 Ma), the northern paleo-Pacific margin had been modified by the accretion of arc and oceanic terranes and was characterized by a major northward reentrant (Fig. 2A). At that time, the Arctic Ocean basin did not exist. During the Early Cretaceous (150–130 Ma), little or no subduction-related magmatism occurred (e.g., Armstrong, 1988). Toward the end of this magmatic lull, North America and Eurasia composed a single plate that rotated clockwise about a pole in northern Scandinavia (Fig. 2).

At ~120 Ma, the subducting Farallon plate changed its motion from oblique to rapid, nearly orthogonal convergence with North America–Eurasia (Engebretson et al., 1985). This change coincided with the opening of the Canada Basin, either by rifting (Fig. 2) or by strike-slip faulting of the Arctic Alaska plate away from the Canadian Arctic Islands (Lawver and Scotese, 1990).

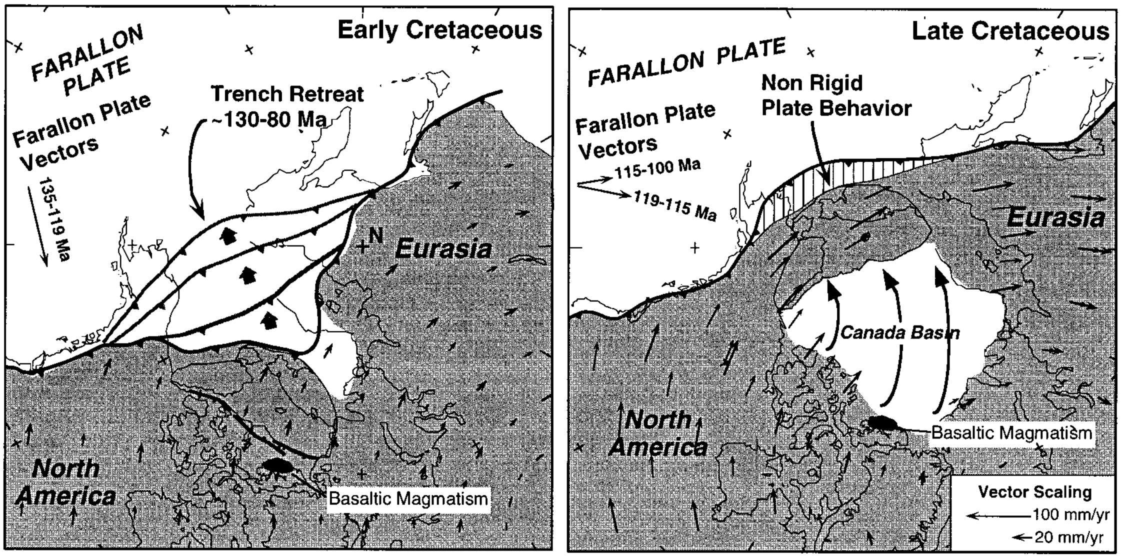

Figure 2. A: Early Cretaceous tectonic configuration of northern circum-Pacific. Local velocity vectors with respect to hotspot frame of reference calculated from poles of Engebretson et al. (1985). Polar orthographic projection used for map base. B: Late Cretaceous plate reconstruction of northern circum-Pacific.

The consequent opening of the Canada Basin was accompanied by retreat of the paleo-Pacific margin out of the Arctic reentrant (Fig. 2B). Magmatism migrated southward with the Arctic Alaska plate, along the submerged Beringian margin (Worrall, 1991), suggesting trench rollback. The relatively old inferred age of the subducting Farallon lithosphere (Engebretson et al., 1985) would have promoted trench rollback, which occurs when the rate of overall plate convergence is less than the rate of subduction and can drive extension in the overriding plate (Dewey, 1980; Otsuki, 1989; Royden and Burchfiel, 1989). In the Canadian Arctic Islands, voluminous Hauterivian to Cenomanian (131–91 Ma) basaltic magmatism, attributed to mantle-plume activity (Embry and Osadetz, 1988), may have controlled the location of initial rifting because of thermal weakening (Fig. 2).

Along the Canadian and southeast Alaska sector of the margin, the rate of convergence exceeded the rate of subduction, resulting in contractional deformation during the Cretaceous. In contrast, along the Russian Far East margin, lack of deformation suggests that convergence kept pace with subduction. The plate model of Engebretson et al. (1985) predicts very little subduction of the Farallon plate under the Russian Far East margin during the Late Cretaceous (Fig. 2B), inconsistent with the development of the Okhotsk-Chukotka magmatic belt.

Variations in deformational style along strike of the Cretaceous circum-Pacific orogenic belt may have been controlled by changes in the mechanical coupling between the subducting oceanic and overriding continental plates. The modern Hellenic subduction system (Royden and Burchfiel, 1989) may represent a smaller-scale modern analogue.

CONCLUSIONS

During the mid- to Late Cretaceous, the northern paleo-Pacific margin was characterized by voluminous intracontinental subduction-related magmatism. The combination of an advancing plate boundary in southeast Alaska and western Canada and a retreating plate boundary in northern Alaska and in Far East Russia explains the variation in large-scale deformation along strike of the plate margin. In the Canadian Cordillera and southeast Alaska, mid-Cretaceous deformation was typified by a protracted history of thrust faulting and crustal thickening followed by uplift and deep erosion that exposed high-grade metamorphic crystalline rocks at the surface. In contrast, in Alaska, the Bering Strait region, and on the Chukotka Peninsula, Russia basin formation and exhumation of high-grade rocks by extensional processes accompanied magmatism. There, southward rollback of the subduction zone out of a reentrant in the plate margin accompanied mantle-derived magmatism and opening of the Canada Basin.

These observations have important implications for helping constrain plate-motion models. Plate-motion data (Engebretson et al., 1985) do not clearly predict the variations in tectonic style developed along strike of the Cretaceous circum-Pacific orogenic belt (Fig. 2). The discrepancy between the observed geologic data and plate-motion models may result from uncertainties in plate-boundary locations or in the time window applied in the plate-motion model.

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REFERENCES CITED

Amato, J., 1995, Tectonic evolution and petrogenesis of the Kigluaik gneiss dome, Seward Peninsula, Alaska: An integrated structural and geochemical study of extensional processes in mid-crustal rocks [Ph.D. thesis]: Stanford, California, Stanford University, 150 p.

Amato, J. M., Wright, J. E., Gans, P. B., and Miller, E. L., 1994, Magmatically induced metamorphism and deformation in the Kigluaik gneiss dome, Seward Peninsula, Alaska: Tectonics, v. 13, p. 515–527.

Armstrong, R. L., 1988, Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, *in* Clark, S. P., Jr., et al., eds., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 55–91.

Arth, J. G., Barker, F., and Stern, T. W., 1988, Coast Batholith and Taku plutons near Ketchikan, Alaska: Petrography, geochronology, geochemistry, and isotopic character: American Journal of Science, v. 2, p. 461–489.

Arth, J. G., Zimuda, C. C., Foley, N. K., Criss, R. E., Patton, W. W., Jr., and Miller, T. P., 1989a, Isotopic and trace element variations in the Ruby batholith, Alaska, and the nature of the deep crust beneath the Ruby and Angayucham terranes: Journal of Geophysical Research, v. 94, p. 15,941–15,955.

Arth, J. G., Zimuda, C. C., Foley, N. K., Criss, R. E., Patton, W. W., Jr., and Miller, T. P., 1989b, Remarkable isotopic and trace element trends in potassic through sodic Cretaceous plutons of the Yukon-Koyukuk Basin in Alaska, and the nature of the lithosphere

beneath the Koyukuk terrane: Journal of Geophysical Research, v. 94, p. 15,957–15,968.
Barnes, D. F., 1977, Bouguer gravity map of Alaska: U.S. Geological Survey Geologic Investigations Map GP-0913, scale 1:2,500,000.
Beaudoin, B. C., Fuis, G. S., Mooney, W. D., and Nockleberg, W. J., 1992, Thin, low-velocity crust beneath the southern Yukon-Tanana terrane, east central Alaska: Results from trans-Alaska crustal transect refraction/wide-angle reflection data: Journal of Geophysical Research, v. 97, p. 1921–1942.
Belyi, V. F., 1973, Okhotsk-Chukotsk fold belt and the problem of volcanic arcs in northeast Asia, *in* Pitcher, Max G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 252–258.
Belyi, V. F., 1994, The Okhotsk-Chukotsk volcanogenic belt: Geology and development: International Conference on Arctic Margins, Magadan, Russia, Abstracts, p. 14.
Box, S. E., and Patton, W. W., 1989, Igneous history of the Koyukuk Terrane, western Alaska: Constraints on the origin, evolution and ultimate collision of an accreted arc terrane: Journal of Geophysical Research, v. 94, p. 15,843–15,868.
Brandon, M. T., Cowan, D. S., and Vance, J. A., 1988, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington: Geological Society of America Special Paper 221, 81 p.
Brown, E. L., 1987, Structural geology and accretionary history of the Northwest Cascades system, Washington and British Columbia: Geological Society of America Bulletin, v. 99, p. 210–214.
Coney, P. J., Jones, D. L., and Monger, J. W., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333.
Crawford, M. L., and Crawford, W. A., 1991, Magma emplacement in a convergent tectonic orogen, southern Revillagigedo Island, southeastern Alaska: Canadian Journal of Earth Sciences, v. 28, p. 929–938.
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.
Dewey, J. F., 1980, Episodicity, sequence and style at convergent plate boundaries, *in* Strangway, D. W., ed., The continental crust and its mineral deposits: Geological Association of Canada Special Paper 20, p. 553–573.
Dumitru, T. A., Miller, E. L., O'Sullivan, P. B., Amato, J. M., Hannula, K. A., Calvert, A. T., and Gans, P. B., 1995, Cretaceous to Recent extension in the Bering Strait region, Alaska: Tectonics, v. 14 (in press).
Dusel-Bacon, C., Brosgé, W. P., Till, A. B., Doyle, E. O., Mayfield, C. F., Reiser, H. N., and Miller, T. P., 1989, Distribution, facies, ages, and proposed tectonic associations of regionally metamorphosed rocks in northern Alaska: U.S. Geological Survey Professional Paper P1497-A, 44 p., 2 maps, scale 1:1,000,000.
Embry, F. A., and Osadetz, K. G., 1988, Stratigraphy and tectonic significance of Cretaceous volcanism in the Queen Elizabeth Islands, Canadian Arctic Archipelago: Canadian Journal of Earth Sciences, v. 25, p. 1209–1219.
Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.
Evenchick, C. A., 1991, Geometry, evolution, and tectonic framework of the Skeena Fold Belt, north-central British Columbia: Tectonics, v. 10, p. 527–546.
Gehrels, G. E., McClelland, W. C., Samson, S. D., Patchett, P. J., and Orchard, M. J., 1992, Geology of the western flank of the Coast Mountains between Cape Fanshaw and Taku Inlet, southeastern Alaska: Tectonics, v. 11, p. 576–585.
Lawver, L. A., and Scotese, C. R., 1990, A review of tectonic models for the evolution of the Canadian basin, *in* Grantz, A., et al., eds., The Arctic Ocean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. L, p. 593–618.
McClelland, W. C., Gehrels, G. E., Samson, S. D., and Patchett, P. J., 1992, Structural and geochronologic relations along the western flank of the Coast Mountains batholith: Stikine River to Cape Fanshaw, central southeastern Alaska: Journal of Structural Geology, v. 14, p. 475–489.
McGroder, M. F., 1989, Structural geometry and structural evolution of the eastern Cascades foldbelt, Washington and British Columbia: Canadian Journal of Earth Sciences, v. 26, p. 1586–1602.
Miller, E. L., and Hudson, T. L., 1991, Mid-Cretaceous extensional fragmentation of a Jurassic–Early Cretaceous compressional orogen: Tectonics, v. 10, p. 781–796.
Miller, E. L., Calvert, A. T., and Little, T. A., 1992, Strain-collapsed metamorphic isograds in a sillimanite gneiss dome, Seward Peninsula, Alaska: Geology, v. 20, p. 487–490.
Miller, R. B., 1985, The ophiolitic Ingalls Complex, north-central Cascade Mountains, Washington: Geological Society of America Bulletin, v. 96, p. 27–42.
Miller, T. P., 1989, Contrasting plutonic rock suites of the Yukon-Koyukuk Basin and Ruby Geanticline, Alaska: Journal of Geophysical Research, v. 94, p. 15,969–15,987.
Natal'in, B. A., 1979, The tectonic nature of the metamorphic rock complex on the Chukotka Peninsula: Geologiya i Geofizika, v. 20, p. 31–38.
Oldow, J. S., Bally, A. W., Ave Lallemant, H. G., and Leeman, W. P., 1989, Phanerozoic evolution of the North American Cordillera: United States and Canada, *in* Bally, A. W., and Palmer, A. R., eds., The geology of North America—An overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 139–231.
Otsuki, K., 1989, Empirical relationships among the convergence rate of plates, rollback rate of trench axis and island-arc tectonics: "Laws of convergence rate of plates": Tectonophysics, v. 159, p. 73–93.
Pavlis, T. L., Sisson, V. B., Foster, H. L., Nokleberg, W. J., and Plafker, G., 1993, Mid-Cretaceous extensional tectonics of the Yukon-Tanana terrane, Trans-Alaska crustal transect (TACT), east-central Alaska: Tectonics, v. 12, p. 103–122.
Roeske, S. M., Walter, M., and Aleinikoff, J. N., 1991, Cretaceous deformation of granitic rocks in the southwest Ruby terrane, central Alaska: Geological Society of America Abstracts with Programs, v. 23, no. 2, p. 93.
Royden, L. H., and Burchfiel, B. C., 1989, Are systematic variations in thrust belt tectonics related to plate boundary processes? (The Western Alps versus the Carpathians): Tectonics, v. 8, p. 51–61.
Rubin, C. M., and Saleeby, J. B., 1992, Tectonic history of the eastern edge of the Alexander terrane, southeast Alaska: Tectonics, v. 11, p. 586–602.
Rubin, C. M., Saleeby, J. B., Cowan, D. S., Brandon, M. T., and McGroder, M. F., 1990, Regionally extensive mid-Cretaceous west-vergent thrust system in the northwestern Cordillera: Implications for continent-margin tectonism: Geology, v. 18, p. 276–280.
Rusmore, M., and Woodsworth, G. W., 1988, A note on the Coast-Intermontane belt transition, Mount Waddington map area, British Columbia, in Current research, Part E: Geological Survey of Canada Paper 89-1E, p. 163–176.
Shul'diner, V. I., and Nedomolkin, V. F., 1976, The crystalline basement of the Eskimos massif: International Geology Review, v. 19, p. 891–902.
Sisson, V. B., Pavlis, T. L., and Dusel-Bacon, C., 1990, Metamorphic constraints on Cretaceous crustal extension in the Yukon crystalline terrane, east-central Alaska: Geological Association of Canada, Joint Annual Meeting, Program with Abstracts, v. 15, p. 122.
Walker, N., and Brown, E. H., 1991, Is the Coast Plutonic Complex the consequence of accretion of the Insular superterrane? Evidence from U-Pb zircon geochronometry in the northern Washington Cascades: Geology, v. 19, p. 714–717.
Worrall, D. M., 1991, Tectonic history of the Bering Sea and the evolution of Tertiary strike-slip basins of the Bering shelf: Geological Society of America Special Paper 257, 120 p.
Zonenshain, L. P., Kuzmin, M. E., and Natapov, L. M., 1990, Geology of the USSR: A plate tectonic synthesis: American Geophysical Union Geodynamics Series, v. 21, 242 p.

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isotopic composition of sectors $\{21\bar{3}1\}$ and $\{2.9.\overline{11}.5\}$ (sector $\{01\bar{1}1\}$ was not considered because of the paucity of data reported for this sector). Results from this test show that there is insufficient evidence ($p < 0.001$) to reject this hypothesis.

In Dickson's Comment, he states that "whether my data are considered from one crystal alone, or collectively from all three, the $\delta^{13}C$ values for $\{21\bar{3}1\}$ equivalent faces consistently are ~2‰ depleted (with considerable scatter) relative to the $\{01\bar{1}1\}$ and $\{2.9.\overline{11}.5\}$ faces." Examination of these data reveals that this statement is not entirely correct. Dickson (1991) pooled data from three different crystals (Bonsall Moor), and assumed that samples from different crystal surfaces were coeval. We performed an analysis of variance ($\alpha = 0.05$) to test the hypothesis of equality of mean isotopic (C and O) composition of sector $\{2.9.\overline{11}.5\}$ for the three crystals:

$$h_0 = \delta^{13}C_A = \delta^{13}C_B = \delta^{13}C_C, \quad (1)$$

where h_0 is the null hypothesis, $\delta^{13}C_A$ is the mean carbon isotopic composition of crystal A, $\delta^{13}C_B$ is the mean carbon isotopic composition of crystal B, and $\delta^{13}C_C$ is the mean carbon isotopic composition of crystal C. Results from this test show significant ($p < 0.01$) difference in both carbon and oxygen isotopic composition between the $\{2.9.\overline{11}.5\}$ faces of the three crystals. This strongly suggests that each crystal ceased growth at different times under different temperature and/or chemical conditions. As such, it is inappropriate to collectively consider data from these three crystals.

Progressive change in the isotopic composition of a crystal may result from change in fluid chemistry and/or temperature. When inner parts of a crystal are isotopically different from outer parts, the crystal is compositionally zoned. Dickson's Abercriban crystal shows such isotopic compositional zoning (our El Paso crystal also shows isotopic compositional zoning), and if the Bonsall Moor crystals show similar compositional zoning, then his sampling procedure could have produced an apparent isotopic sector zoning effect even if none existed. For example, because growth rate on crystal face $\{2.9.\overline{11}.5\}$ exceeded that of crystal face $\{21\bar{3}1\}$, sampling to equal depths on the two faces results in samples that are not synchronous, and, on average, would have been precipitated under different temperature and/or chemical conditions. Consequently, samples from such nonequivalent faces would yield dissimilar results, and one would expect to "discover" an apparent isotopic sector zoning effect where none existed.

Inasmuch as our analyses on a single crystal are representative of all calcite, which crystallizes under a multitude of conditions and in different forms, we found no evidence for carbon or oxygen isotopic sector zoning. Given this, and in light of theoretical considerations that argue against isotopic sector zoning (Klein and Lohmann, 1995); the inconsistencies between oxygen isotope data and previous interpretations (Dickson, 1991), in addition to the sampling technique used in that study, it is reasonable to continue to question the existence of isotopic sector zoning in calcite.

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REFERENCES CITED

Dickson, J. A. D., 1991, Disequilibrium carbon and oxygen isotope variations in natural calcite: Nature, v. 353, p. 842–844.

Klein, R. T., and Lohmann, K. C., 1995, Isotopic homogeneity among non-equivalent sectors of calcite: Geology, v. 23, p. 633–636.

CORRECTION

Deformation of the northern circum-Pacific margin: Variations in tectonic style and plate implications: Correction
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Figure 2 was published with a drafting error. The size of some of the vectors on the continental plates is wrong. This is the corrected Figure 2.

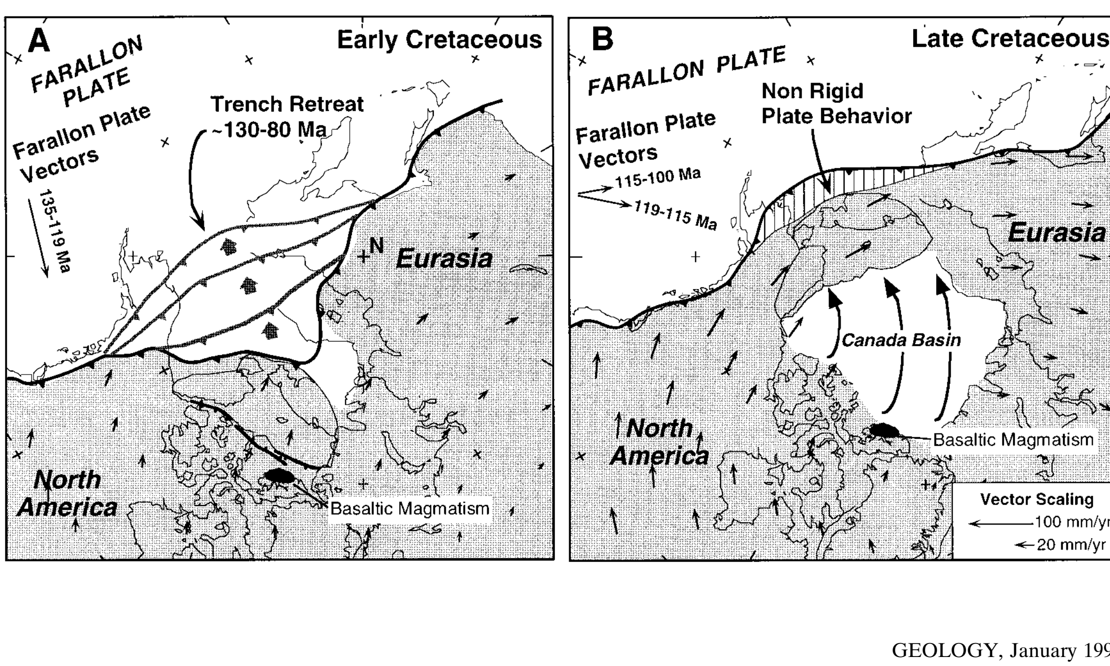

Figure 2. A: Early Cretaceous tectonic configuration of northern circum-Pacific. Local velocity vectors with respect to hotspot frame of reference calculated from poles of Engebretson et al. (1985). Polar orthographic projection used for map base. B: Late Cretaceous plate reconstruction of northern circum-Pacific.