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Chapter 20

Crustal melting events in Alaska

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INTRODUCTION

Development of granitic magmas by melting of continental crust is documented by field studies in migmatite terranes (e.g., Kenah and Hollister, 1983; Johannes and Gupta, 1982), petrologic and mineralogic studies (e.g., White and Chappell, 1977; Speer, 1981; Wright and Haxel, 1982), geochemical and isotopic studies (e.g., Ben Othman and others, 1984; Kistler and others, 1981; Arth, this volume), and experimental studies (e.g., Clemens and Wall, 1981; Wyllie, 1983a). Although the processes that lead to melting of continental crust are complex (e.g., Leake, 1983), where present, these events are obviously an important element in the geologic evolution of a region. One expected result of such an event is the regional emplacement of felsic granitic rocks.

In this chapter, any granitic rocks whose composition can be inferred to be predominantly derived from sialic crustal materials—even juvenile crustal materials as is the case for some accretionary parts of southern Alaska—are considered to be the products of crustal melting. However, generally accepted criteria for recognizing such granitic rocks, such as high initial $^{87}Sr/^{86}Sr$, peraluminous composition, restite minerals or inclusions, and relations to metamorphism and migmatization, are generally not available for most granitic rocks in Alaska. For this reason, and because in some settings the distinctions between mantle and crustal processes are blurred (e.g., Leeman, 1983; Wyllie, 1983b; Ben Othman and others, 1984), a simplistic approach is taken here. The two principal criteria used to distinguish Alaskan granitic rocks whose origin may have been dominated by crustal melting processes are: (1) the compositional variation is dominantly restricted to granodiorite and granite, and (2) the granodiorite and granite represent temporally distinct, regionally distributed, plutonic events. These criteria can be supported by additional evidence, such as field relations, high initial $^{87}Sr/^{86}Sr$ ratios, and the presence of inherited zircons, in some cases. Based on the general criteria, widespread crustal melting in Alaska took place primarily in the Devonian, Cretaceous, and Paleogene. The distribution (all physiographic place names follow Wahrhaftig, this volume), age (all geologic time subdivisions follow Palmer, 1983), general character, and regional setting of the granitic rocks developed during each of these melting events is summarized separately below. These relations, combined with other aspects of the regional geology, enable the tectonic setting in which the crustal melting took place to be inferred. The inferred settings are different for the Devonian and Cretaceous events as well as for the two subdivisions of the Paleogene event.

DEVONIAN ORTHOGNEISSES

Granitic orthogneisses (Fig. 1) are exposed on Seward Peninsula (Till, 1983; Till and Dumoulin, this volume), in the Brooks Range (Nelson and Grybeck, 1980; Silberman and others, 1979a; Dillon and others, 1980; Sable, 1977; Moore and others, this volume), in the Ruby geanticline (Dover, 1984; W. W. Patton, oral communication, 1984; Patton and others, this volume, Chapter 7), and in the Yukon-Tanana Upland (Aleinikoff and others, 1981; Dusel-Bacon and Aleinikoff, 1985; Foster and others, this volume). Similar orthogneiss bodies are present in the Yukon Territory (Tempelman-Kluit and Wanless, 1980; Mortensen, 1983). The emplacement ages of the Alaska plutons as indicated by whole-rock Rb/Sr and zircon U/Pb ages, range from 344 ± 3 to 381 ± 6 Ma. They are primarily Devonian, although some in the Yukon-Tanana Upland are Mississippian (Dusel-Bacon and Aleinikoff, 1985).

The orthogneisses form subequant to irregular bodies (up to 35 km across) that are emplaced into metasedimentary country rocks of Precambrian(?) and early Paleozoic age. The orthogneisses have been variably metamorphosed to greenschist (Adams, 1983) and amphibolite facies (Dusel-Bacon and Aleinikoff, 1985; Dusel-Bacon, this volume), and the strong foliation developed within them is commonly concordant with the regional structural trends in their country rocks. Nevertheless, in places, sharp discordant contacts, apophyses and dikes into country rocks, and the presence of marginal hornfels and skarn, document the original intrusive character of these bodies (Adams, 1983; Sable, 1977). Original granitic features such as texture, schlieren, xenoliths, jointing, and aplitic and pegmatitic dikes are also preserved in some locations.

These metaplutonic rocks are medium- to coarse-grained, strongly foliate to gneissic, equigranular to blastoporphyritic, biotite (± muscovite) metagranite, and less abundant metagranodiorite and siliceous metatonalite. The accessory minerals now present are commonly zircon, apatite, garnet, sphene, ilmenite, and epidote-group minerals. The major-oxide data available for

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these rocks (Fig. 2) confirm their dominantly felsic character: silica varies from 67 to 78 percent, the combined Fe_2O_3 + FeO + MgO + CaO content varies from 0.7 to 7.9 percent, total alkalies vary from 6.1 to 8.5 percent, and the average K_2O/Na_2O ratio is about 1.6. The major-oxide variations primarily reflect decreasing mafic oxide contents with increasing silica; K_2O increases slightly with increasing silica. Rb/Sr isotopic data for the Arrigetch Peaks and Mount Igikpak plutons in the south-central Brooks Range indicate an initial $^{87}Sr/^{86}Sr$ ratio of 0.714 ± 0.003 (Silberman and others, 1979a), and similar data for augen gneiss bodies in the Yukon-Tanana Upland give initial $^{87}Sr/^{86}Sr$ ratios of 0.719 and 0.728 (Aleinikoff and others, 1986; Dusel-Bacon and Aleinikoff, 1985). Inherited zircons are locally present both in the Brooks Range and Yukon-Tanana Upland orthogneisses (Aleinikoff and others, 1981, 1986; J. T. Dillon, oral communication, 1984).

Thus, the available data support the interpretation that the Devonian orthogneisses of interior and northern Alaska represent anatectic melts of sialic crust. The regional relations listed below are important for interpreting the tectonic setting in which Devonian crustal melting took place.

1. The anatectic magmas intruded sialic crust upon which marine (meta)sedimentary sequences of early Paleozoic and, in places, possibly older age were deposited. Where the Yukon-Tanana Upland extends into Canada, these metasedimentary sequences probably represent the early Paleozoic or older continental margin of North America (Tempelman-Kluit, 1979).

2. Marine mafic and felsic metavolcanic rocks that have been documented as, or inferred to be of, Devonian age (Smith

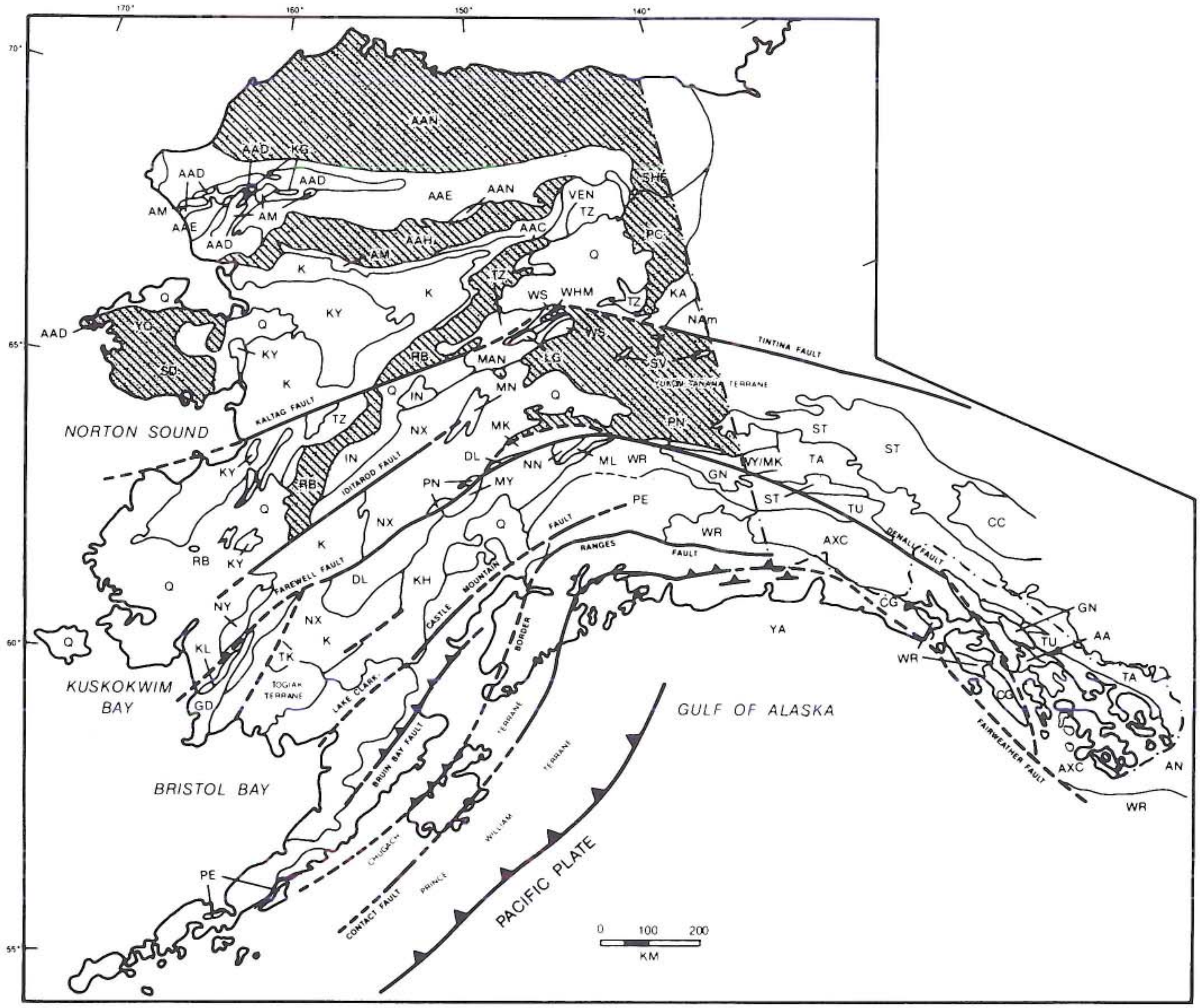

Figure 1. Map showing tectonostratigraphic terranes in Alaska (boundaries and symbols follow Jones and others, 1987; also see Silberling and others, this volume); shaded areas show the terranes that are known or suspected to contain Devonian and earliest Mississippian orthogneiss.

and others, 1978; Dillon and others, 1980; Aleinikoff, 1984; Aleinikoff and others, 1986; Duke and others, 1984; Hitzman, 1984) also developed in the regions where the Devonian orthogneisses were emplaced.

3. The metamorphic history of the regions containing the Devonian orthogneisses is not well known, but regional dynamothermal metamorphism appears to have taken place primarily in the Mesozoic and not the Devonian (Till, 1983; Forbes and others, 1984a, 1984b; Dillon and others, 1980; Dover, 1984; Cushing and others, 1984).

Previous interpretations of the tectonic setting for Devonian magmatism in Alaska fall into two categories: development of a convergent margin or island magmatic arc (Dillon and others, 1980; Nokleberg and others, 1983; Lange and Nokleberg, 1984; Dusel-Bacon and Aleinikoff, 1985) or development of extensional regions and marginal basins (Schmidt, 1984; Hitzman, 1984; Duke and others, 1984; Gemuts and others, 1983). In light of the regional relations listed above, and the observation that plutons developed in convergence-related magmatic arcs are more varied in composition than granodiorite and granite (e.g., Hudson, 1983), the interpretation preferred here is that the Devonian granites were emplaced in an extensional and/or transcurrent tectonic setting. If so, the extensional thinning of the continental crust, accompanied by emplacement of mafic magmas, could have led to high heat flow and anatectic melting.

CRETACEOUS GRANITIC ROCKS

The character of Cretaceous magmatic rocks in Alaska (Miller, this volume) is varied, but several suites of Cretaceous granodiorite and granite plutons (Fig. 3) may be the products of crustal melting. These include plutons on Seward Peninsula (Miller and Bunker, 1976; Hudson, 1977; Hudson and Arth, 1983), in the Ruby geanticline (Patton and Miller, 1973; Chapman and others, 1982; Silberman and others, 1979b; Puchner, 1984), and the Yukon-Tanana Upland and nearby parts of the Alaska Range (Forbes, 1982; Foster and others, 1978; Foster, 1976; Foster and others, 1979; Luthy and others, 1981; Foster and others, 1976; Foster, 1970; Richter and others, 1975; Richter, 1976; Blum, 1985). Plutons similar to those in the Yukon-Tanana Upland are present in the Yukon Territory of Canada (Tempelman-Kluit and Wanless, 1975). The reported K/Ar ages for these rocks (Wilson and others, this volume) range from 70 to 94 Ma on Seward Peninsula, from 91 to 111 Ma in the Ruby geanticline, and from 84 to 110 Ma in the Yukon-Tanana Upland and the Alaska Range. The similar plutons in the Yukon Territory give K/Ar ages in the 90 to 100 Ma range.

Several of the Cretaceous plutons are large (as much as 60 km across), subequant to elongate bodies that are emplaced into a regional assemblage of amphibolite-facies, metasedimentary and metavolcanic rocks of Precambrian(?) and Paleozoic age. These larger plutons display such mesozonal contact relations as grossly concordant foliated margins and broad irregular contact zones characterized by abundant dikes and sills in the country rocks. Smaller and more shallowly emplaced plutons, such as those on western Seward Peninsula, have sharp crosscutting contacts and distinct thermal aureoles in country rocks that are of low metamorphic grade or, in places, not metamorphosed.

The plutons are composite intrusions that are composed primarily of medium- to coarse-grained, equigranular to porphyritic biotite granite. Porphyritic granite containing large (several centimeters long) K-feldspar phenocrysts in a coarse-grained groundmass underlies large areas; porphyritic granite containing quartz, K-feldspar, and plagioclase phenocrysts in a fine-grained aplitic groundmass underlies smaller areas. Fine- to medium-grained equigranular granite occurs locally, both as marginal fa-

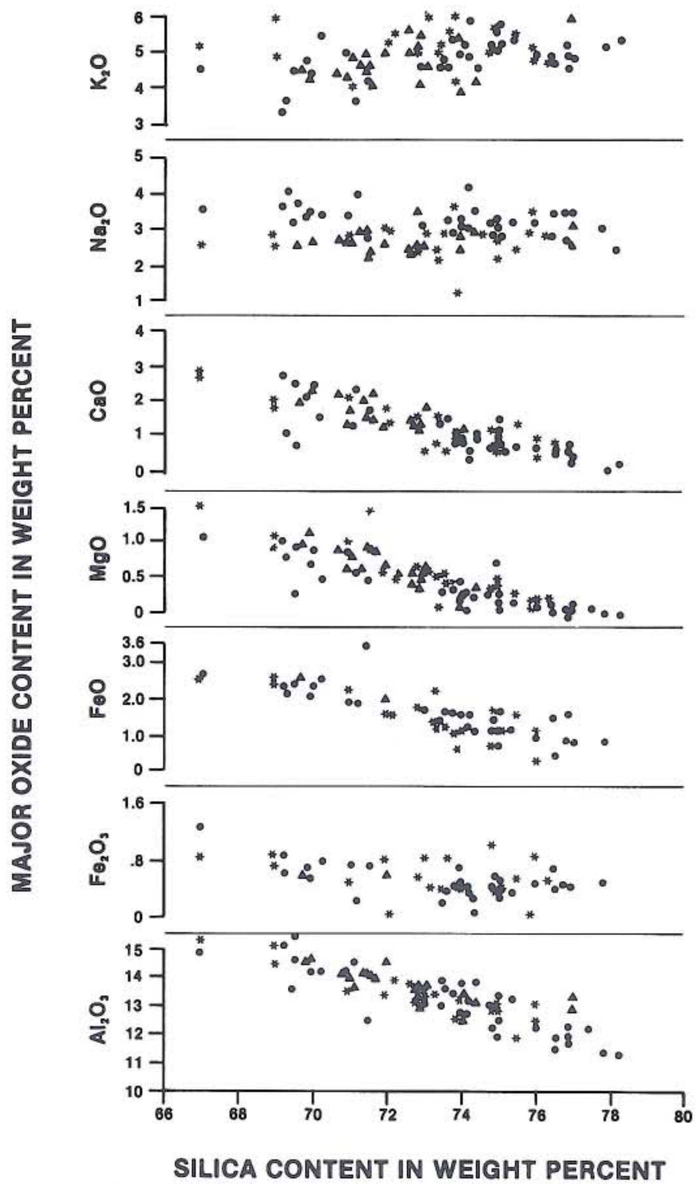

Figure 2. Variation of major oxides with silica content for orthogneisses from the Survey Pass Quadrangle in the south-central Brooks Range (●), the Okpilak batholith in the northeastern Brooks Range (*), and the Yukon-Tanana Upland (▲). See text for sources of data.

cies and as late intrusions. In general, biotite granodiorite and hornblende-biotite granodiorite are less common than granite, except for the plutons in the Yukon-Tanana Upland, where many of the samples described by Foster and others (1978) and Luthy and others (1981) are granodiorite. The accessory minerals commonly are zircon, apatite, sphene, allanite, and magnetite or ilmenite. The magnetite and ilmenite content is variable within some plutons (e.g., the Oonatut Granite Complex on Seward Peninsula: Hudson, 1979a; Hudson and Arth, 1983) and between batholiths (e.g., Darby and Bendeleben batholiths; Miller and Bunker, 1976).

Major-oxide contents (Fig. 4) have been determined for selected plutons on Seward Peninsula (Hudson and Arth, 1983; T. P. Miller, unpublished data), in the Ruby geanticline (C. Puchner, 1984, and unpublished data), and in the Yukon-Tanana Upland (Forbes, 1982; Foster and others, 1978; Luthy and others, 1981; Blum, 1985). In the Yukon-Tanana Upland, only Blum (1985) and Luthy and others (1981) have identified and described mid-Cretaceous plutons separately from other granitic rocks in this region. For this reason, only the petrologic and major-oxide data for two plutons in the Eagle Quadrangle (Foster and others, 1978) are included here. These plutons are located between the Shaw Creek and Mt. Harper lineaments (Wilson and others, 1985). They have been mapped as continuous intrusive bodies (Foster, 1976), and samples from two widely scattered localities within them give mid-Cretaceous K/Ar ages (Wilson and others, 1985).

On Seward Peninsula and in the Ray Mountains pluton of the Ruby geanticline (Fig. 4), silica varies from 68 to 77 percent,

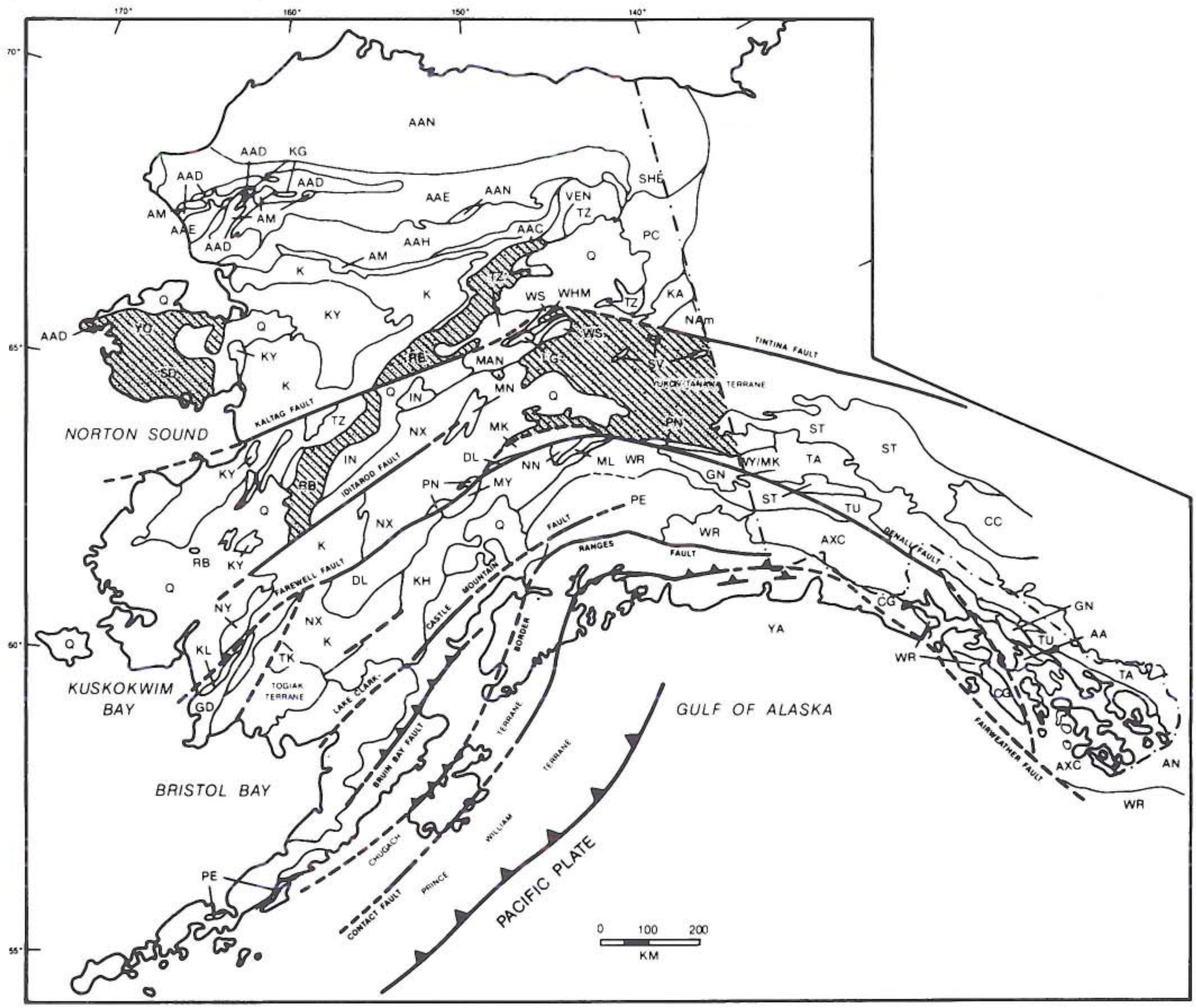

Figure 3. Map showing tectonostratigraphic terranes in Alaska (boundaries and symbols follow Jones and others, 1987; also see Silberling and others, this volume); shaded areas show the terranes that contain crustally derived Cretaceous granodiorite and granite.

total FeO + Fe_2O_3 + MgO + CaO varies from 0.5 to 3.5 percent, and total alkali content varies from 6.7 to 9.0 percent with a K_2O/Na_2O ratio of 1.1 to 1.8. The data for the Yukon-Tanana Upland indicate silica variation from 59 to 77 percent, total FeO + Fe_2O_3 + MgO + CaO content between 2.1 and 17.2 percent, and total alkalies ranging from 4.8 to 8.2 percent with a K_2O/Na_2O ratio of 0.7 to 2.0. Major-oxide variation within these plutons primarily reflects decreasing mafic oxide contents with increasing silica and alkalies. The Yukon-Tanana Upland plutons exhibit more compositional variation than the other Cretaceous plutons included in this study (Fig. 4), reflecting an increase of granodiorite in this region. The most mafic samples (<63 percent SiO_2) are from small plutons in the Fairbanks area that contain mafic xenoliths and minor amounts of pyroxene (Blum, 1985). Limited isotopic data (Hudson and Arth, 1983; Arth and others, 1984; Puchner, 1984; Blum, 1985) indicate initial $^{87}Sr/^{86}Sr$ ratios between 0.708 and 0.730 for the Cretaceous plutons; one lower value of 0.706 has a large uncertainty associated with it (Hudson and Arth, 1983). This isotopic variability suggests heterogeneous source regions for the magmas.

The regional relations important for interpreting the tectonic setting in which mid-Cretaceous crustal melting took place are listed below and summarized diagrammatically in Figure 5.

1. Jurassic and/or Early Cretaceous regional progressive metamorphism of high-pressure-facies series, and/or strong compressive deformation including thrust faulting, affected the Seward Peninsula (Till, 1983, 1984; Forbes and others, 1984a, b), the southern Brooks Range (Forbes and others, 1984a; Hitzman, 1982), the Ruby geanticline (Dover, 1984), and the Yukon-Tanana Upland (Brewer and others, 1984; Brown and Forbes, 1984; Cushing and others, 1984). The age of this deformation and metamorphism is not conclusively known, but it could be mostly Late Jurassic in age.

2. Late Early Cretaceous retrograde recrystallization of the high-pressure metamorphic rocks developed on Seward Peninsula (Forbes and others, 1984b) and the southern Brooks Range (Turner and others, 1979). Important regional recrystallization also took place in the Yukon-Tanana Upland (Wilson and others, 1985) and probably in the Ruby geanticline during the Early Cretaceous.

3. Early Cretaceous andesitic volcanism was widespread in the Yukon-Koyukuk province (Patton, 1973). An intermediate composition plutonic suite, associated with subsilicic and K_2O-rich intrusive rocks, was also emplaced in this region (97 to 108 Ma; Miller, 1972), while Cretaceous granodiorite and granite were emplaced elsewhere in Alaska.

4. Albian and younger Cretaceous sedimentation filled large successor basins of interior Alaska. These thick sections were deposited in deep marine to brackish-water environments.

5. Mid-Cretaceous (100 to 110 Ma) calc-alkaline magmatism, probably related to subduction, is present in the east-central Alaska Range (Richter and others, 1975; Hudson, 1979b).

6. Late Cretaceous magmatism occurred in the Alaska Range concurrently with fore-arc sedimentation in the Matanuska Valley and Cook Inlet and with accretion along the Gulf of Alaska margin (Hudson, 1979b). Late Cretaceous to earliest Tertiary calc-alkaline and related magmatism was widespread throughout interior Alaska and nearby parts of the Yukon Territory (Bergman and others, 1987).

The above events may reflect collisional, extensional, or subduction-related tectonic processes (Fig. 5). To understand the origins of mid-Cretaceous crustal melting, those processes that could emplace mantle-derived magma into the crust need to be considered first. The magmatism that may reflect these processes includes the Early Cretaceous andesitic volcanism and mid-Cretaceous plutonism of the Yukon-Koyukuk province and the

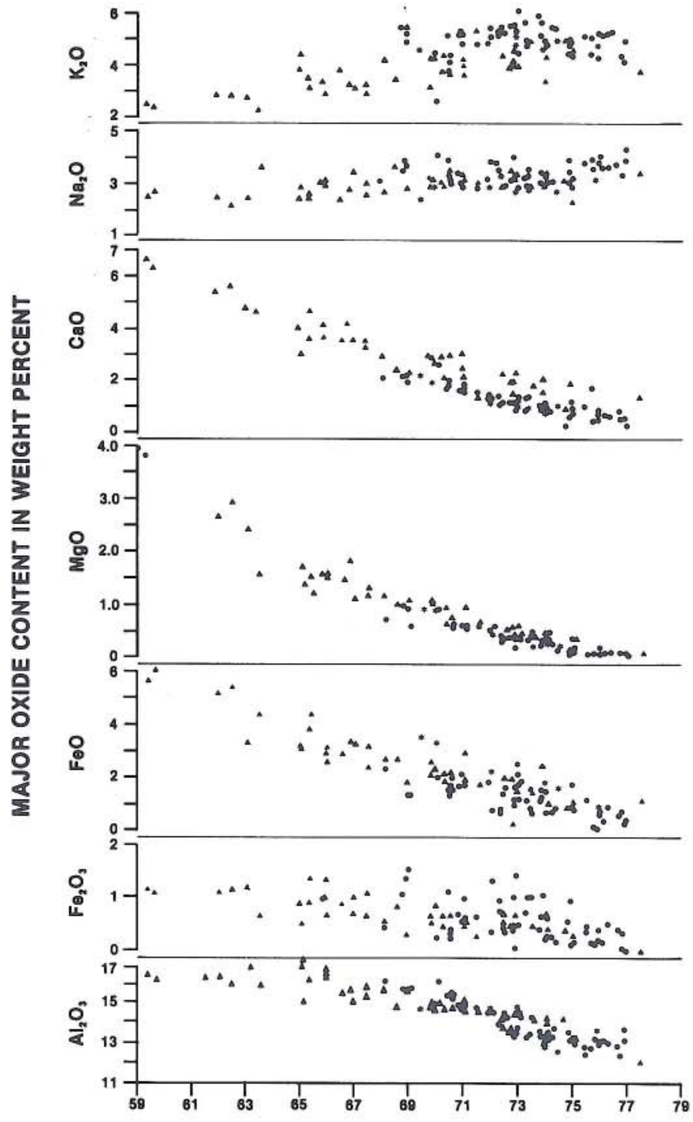

Figure 4. Variation of major oxides with silica content for Cretaceous granodiorite and granite from Seward Peninsula (●), the Ray Mountains pluton in the Ruby geanticline (*; FeO = total iron), and the Yukon-Tanana Upland (▲). See text for sources of data.

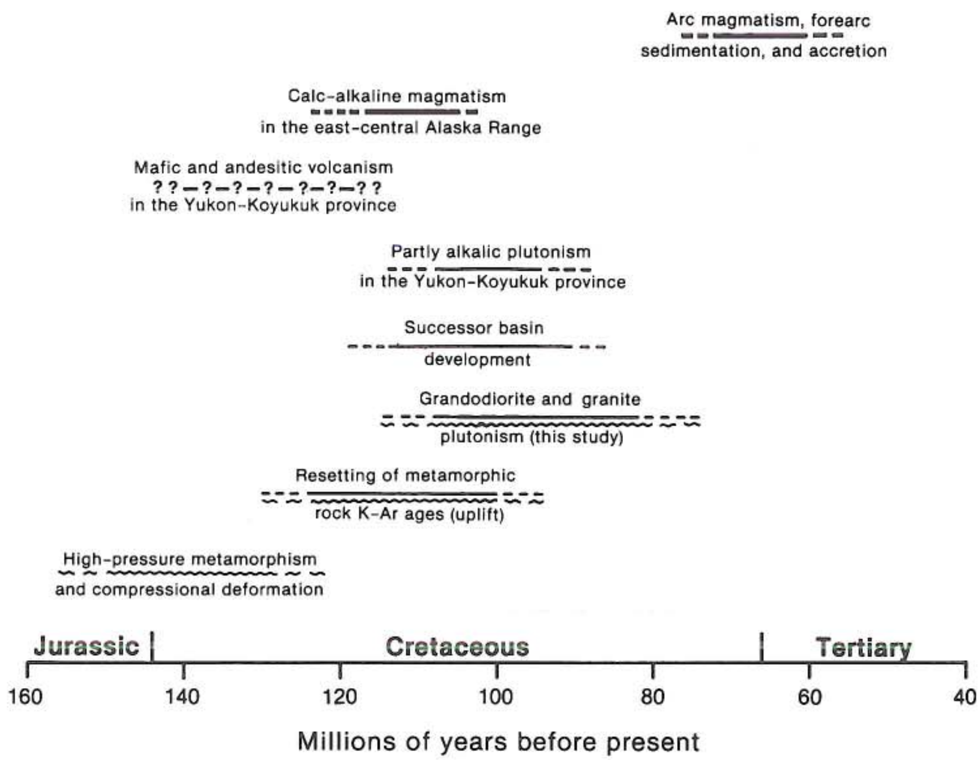

Figure 5. Diagrammatic summary of some major tectonic events bearing on the Cretaceous evolution of Alaska. These events are here linked to collisional (~), extensional (–), subduction (▬), or unknown (?-?) tectonic processes. The overlap in collisional and extensional events is interpreted here to represent an orogenic cycle of compression and subsequent decompression that affected all of interior Alaska in the Early to mid-Cretaceous. This interpretation implies that the Early Cretaceous volcanism of the Yukon-Koyukuk province may not be subduction related, although understanding its origin awaits further study.

mid-Cretaceous calc-alkaline magmatism of the east-central Alaska Range. The Late Cretaceous and Early Tertiary magmatism postdates the mid-Cretaceous granodiorite and granite plutonism of special concern here.

The Early Cretaceous volcanism and mid-Cretaceous plutonism of the Yukon-Koyukuk province are somewhat enigmatic in the regional geology of interior Alaska. The interpretation favored by some (e.g., Box, 1985) is that the volcanic assemblage represents an intraoceanic, subduction-related magmatic arc that was accreted to North America and is therefore allochthonous with respect to adjacent regions. If so, then this Early Cretaceous volcanism is not necessarily evidence of heat flux from the mantle in interior parts of Alaska. The mid-Cretaceous alkalic and related plutonism of the Yukon-Koyukuk province, however, suggests some mantle-related heat flux in interior Alaska, although as presently known, the plutons are restricted to the Yukon-Koyukuk province, nearby parts of Seward Peninsula, and St. Lawrence Island (Patton and Csejtey, 1980).

The calc-alkaline magmatism of the east-central Alaska Range is probably subduction related and could be the outer part of the magmatic arc that extended inland to include other mid-Cretaceous igneous rocks of the Canadian Cordillera (e.g., Le-Couteur and Tempelman-Kluit, 1976). If so, then mantle-derived magma could be responsible for some of the compositional variability of the Yukon-Tanana Upland granodiorites or for heating of deeper parts of the crust that contributed to abundant crustal melting in the Yukon-Tanana Upland (Blum, 1985). The influence of this possibly subduction-related magmatism appears to be restricted to east-central Alaska inasmuch as mid-Cretaceous magmatic rocks similar to those in the east-central Alaska Range have not been identified farther west. An adequately constrained interpretation of these regional relations will require careful reconstruction of the major strike-slip displacements on the Tintina and Denali fault systems.

Early and mid-Cretaceous mantle-related magmatism and an accompanying heat flux thus may have contributed to crustal melting in or near the Yukon-Koyukuk province and in east-central Alaska. However, it is the conclusion of this study that the most striking and widespread characteristics of the middle Mesozoic history of interior Alaska are (1) the Late Jurassic or Early Cretaceous high-pressure metamorphism, (2) mid-Cretaceous retrograde (uplift) recrystallization of the high-pressure metamorphic rocks, (3) mid-Cretaceous deep successor basin formation and filling, and (4) mid-Cretaceous voluminous granodiorite and granite emplacement (Fig. 5). The interpretation of these regional events that is preferred here is that a major Late Jurassic or Early Cretaceous period of compressional (collision-related?) deformation over large parts of interior Alaska significantly thickened the crust by structural imbrication, thus producing regionally distributed high-pressure metamorphic rocks. Crustal thickening and accompanying high-pressure metamorphism were followed by the reestablishment of thermal gradients in the lower crust and uplift as recorded by the widespread mid-Cretaceous retrograde recrystallization and resetting of K-Ar ages in metamorphic rocks. Melting in deeper parts of this uplifted crust probably took place at this time together with the extension necessary for development of the deep successor basins and for emplacement of any mantle-derived alkalic and associated magmas in the Yukon-Koyukuk province, Seward Peninsula, and St. Lawrence Island. The dominant tectonic processes leading to widespread mid-Cretaceous crustal melting in interior Alaska are therefore interpreted here to be the development of a compressional orogen and its subsequent extensional collapse. This interpretation implies that the Early Cretaceous mafic and andesitic volcanism of the Yukon-Koyukuk province may not reflect classic intraoceanic subduction, and that its origin deserves further study.

PALEOGENE GRANITIC ROCKS

Three belts of Paleogene granitic rocks (Fig. 6) appear to have an origin dominated by crustal melting. These include the McKinley sequence (Reed and Lanphere, 1973) and similar plutons elsewhere in the Alaska Range–Talkeetna Mountains belt (Hudson, 1983), the Sanak-Baranof belt along the Gulf of Alaska margin (Hudson and others, 1979; Hudson, 1983), and the Coast Mountains belt of southeastern Alaska (Coast Plutonic Complex belt I of Brew and Morrell, 1983; Brew, this volume). The K/Ar ages of these rocks vary from about 50 to 58 Ma in the Alaska Range–Talkeetna Mountains belt, from 58 to 60 Ma in the western segment and 45 to 52 Ma in the eastern segment of the Sanak-Baranof belt, and from about 45 to 54 Ma in the Coast Mountains belt.

The field and petrologic characteristics of the Paleogene granitic rocks in the Alaska Range–Talkeetna Mountains and Sanak-Baranof belts have been summarized by Hudson (1979b, 1983), Hudson and others (1979), and Hudson and Plafker (1982). The Paleogene plutons of the Coast Mountains belt form large subequant and coalescing plutons that are emplaced at shallow depths. The contacts are discordant to the deep-seated metamorphic and plutonic host rocks as well as to the low-grade metasedimentary and metavolcanic rocks that flank the Coast Mountains to the east. These plutons are dominantly massive, medium- to coarse-grained, equigranular biotite granite and granodiorite containing minor amounts of accessory hornblende, sphene, and, in some, garnet.

Major-oxide (Fig. 7) and other chemical data are available for the McKinley sequence in the Alaska Range (Reed and Lanphere, 1973, 1974a; Lanphere and Reed, 1985), some plutons of the Sanak-Baranof belt (Hill and others, 1981; Hudson and others, 1977), and for a number of plutons in the Coast Mountains belt (Barker and others, 1986; Smith and others, 1977). The analyses of the Paleogene granites of the Alaska Range–Talkeetna Mountains belt have an average SiO_2 content of 74.3 percent (range is 65.9 to 77.6 percent), an average CaO content of 1.1 percent (range is 0.34 to 2.9 percent), and an average $K_2O + Na_2O$ content of 8 percent. The average $K_2O + Na_2O$ ratio is 1:4. The analytical data for the Sanak-Baranof belt plutons show a wide range of compositional variation: SiO_2 ranges from 51 to 76 percent, Fe_2O_3* (total iron) + MgO + CaO from 1.9 to 10.9 percent and $K_2O + Na_2O$ from 5.9 to 8.6 percent. K_2O/Na_2O ratios are 0.6 to 2.0 (mostly about 1). The available data for the Coast Mountains belt (Barker and others, 1986; Smith and others, 1977) show a range of SiO_2 content from 53 to 77 percent (mostly 65 to 72 percent), a total FeO + Fe_2O_3 + MgO + CaO content of 2.8 to 16.0 percent (mostly <10 percent), and a $K_2O + Na_2O$ content of 6.3 to 8.5 percent; K_2O/Na_2O ratios are 0.4 to 1.6. The more mafic compositions in the Coast Mountains belt and the Sanak-Baranof belt are of sparse (only 11 percent of the samples have silica contents lower than 64 percent; Fig. 7), strongly foliated, hornblende-bearing rocks that in part include schlieren-like features. These more mafic rocks are present in places where mixing of amphibolitic country rocks with the granitic magma during emplacement can be inferred (e.g., the Mt. Draper and Mt. Stamy plutons in the Yukutat–St. Elias area; Hudson and others, 1977, p. 166). The available Sr isotope data (Lanphere and Reed, 1985; Hill and others, 1981; Hudson and others, 1979; Barker and others, 1986) all indicate initial $^{87}Sr/^{86}Sr$ ratios between 0.7048 and 0.7085. These values are consistent with those measured or inferred for the youthful, partly transitional continental margin crust (accreted deep sea sedimentary sequences and oceanic basalt) that underlies much of southern Alaska (Hill and others, 1981; Hudson and others, 1979).

The regional relations listed below are important for interpreting the tectonic setting in which Paleogene crustal melting took place (Plafker and Berg, this volume, Chapter 33).

1. A Late Cretaceous and earliest Tertiary calc-alkaline magmatic arc developed in the Alaska Range–Talkeetna Mountains region and in the Coast Mountains (Reed and Lanphere, 1973; Hudson, 1979b; Barker and others, 1986; Brew and Morrell, 1983).

2. Late Cretaceous and earliest Tertiary high-grade regional metamorphism and migmatization took place in the deeper parts of the Alaska Range and Talkeetna Mountains region (Smith, 1981, 1984) and the Coast Mountains (Kenah and Hollister, 1983; Brew and Ford, 1984). Such metamorphism and migmatization took place in the Gulf of Alaska region some time during the Paleocene or earliest Eocene (between 50 Ma and the time of accretion of the Upper Cretaceous flysch of the Valdez Group; Hudson and Plafker, 1982).

3. Right-lateral displacement of a few hundred kilometers along the principal strand of the Denali fault system may juxtapose similar Late Cretaceous and early Tertiary metamorphic and plutonic rocks of the Alaska Range and the Coast Mountains

(Forbes and others, 1974; Turner and others, 1974). Even if post–Late Cretaceous displacement on the Denali fault is tens of kilometers (Reed and Lanphere, 1974b; Csejtey and others, 1982), Figure 6 shows that the two northern plutonic belts are nearly connected and subparallel to the coeval Sanak-Baranof belt to the south.

The tectonic setting that immediately preceded emplacement of the Paleogene granitic rocks is well defined. In latest Cretaceous time, southern Alaska had a convergent subduction margin, as evidenced by development of a calc-alkaline magmatic arc, a fore-arc basin, and an accretionary complex seaward of the Border Ranges fault (Fig. 6).

The calc-alkaline magmatic front that was developed during this tectonic regime roughly coincides with the Alaska Range–Talkeetna Mountains and Coast Mountains belts of Paleogene plutons. The preferred interpretation here is that subduction-related magmatism had ceased by 60 Ma and that the 45 to 58-Ma granodiorite and granite plutons in these belts are post-subduction plutons whose origin is ultimately due to high-heat flow that accompanied the slightly older subduction-related magmatism. This origin for the Alaska Range–Talkeetna Mountains and Coast Mountains belts of Paleogene granodiorite and granite plutons seems much more likely than the accretionary origin for the McKinley sequence suggested by Lanphere and

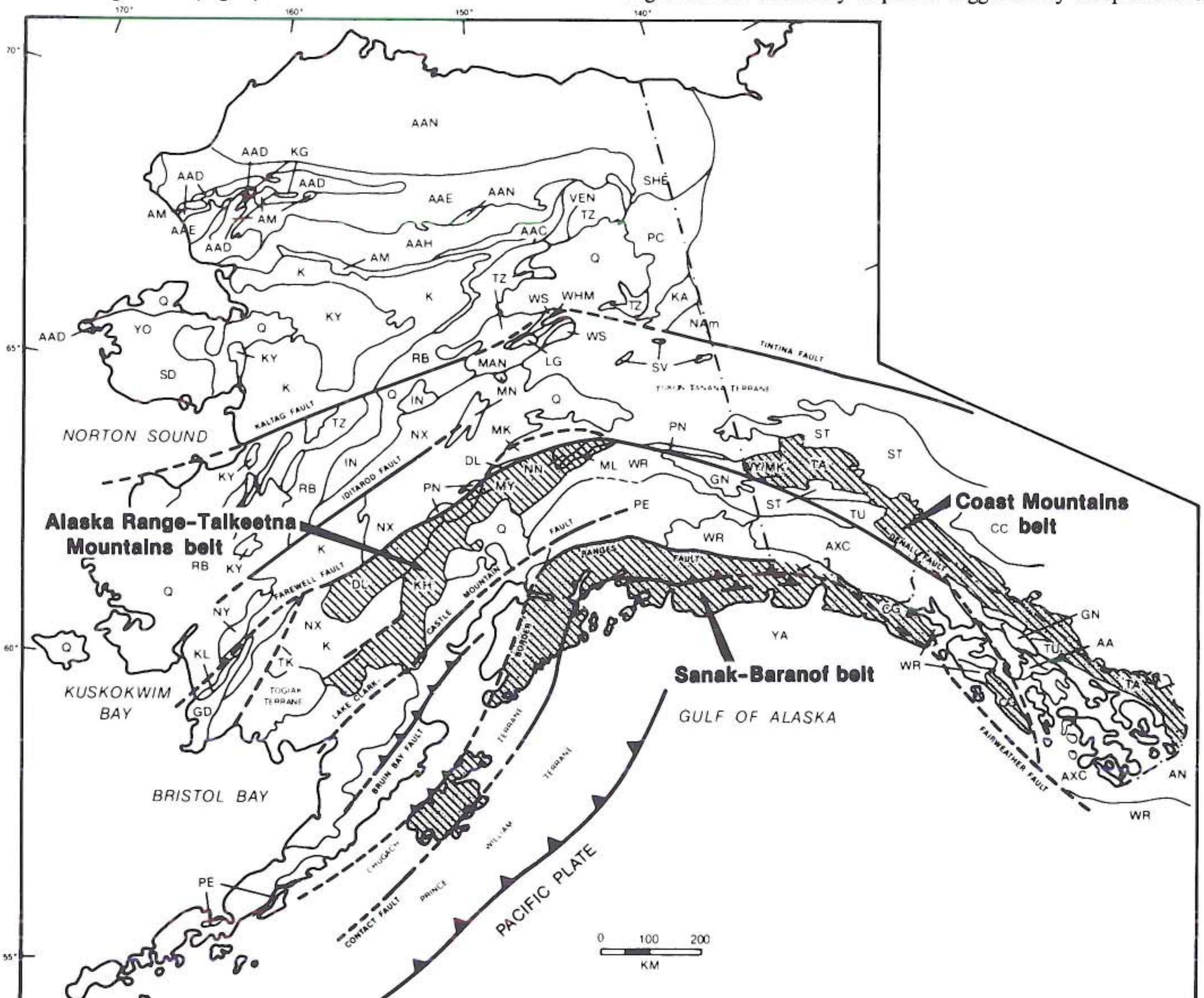

Figure 6. Map showing onshore extent of principal tectonostratigraphic terranes in Alaska (boundaries and symbols follow Jones and others, 1987; also see Silberling and others, this volume). Shaded areas show the terranes that contain crustally derived Paleogene granodiorite and granite. The Paleogene plutons in these terranes define three plutonic belts as indicated. Small dikes and plugs of similar granitic rocks are present in the upper plate of the Border Ranges fault (PE terrane) and locally within Wrangellia (WR terrane).

Reed (1985)—especially in light of the petrologic character of some composite plutons in the Alaska Range that show evidence of magma mixing. These composite 65-Ma plutons are mostly quartz monzonite, but they range in composition from peridotite to granite and contain such unusual components as K-feldspar-bearing ultramafic rocks and olivine-bearing pyroxene quartz monzonite (Reed and Nelson, 1980). These components strongly suggest that mantle-derived magmas were emplaced into the crust and incompletely mixed with felsic crustal melts. This interpretation also is consistent with the results of studies in the British Columbia part of the Coast Mountains belt just south of the area shown in Figure 6 (Kenah, 1979; Hollister, 1982; Crawford and Hollister, 1982; Kenah and Hollister, 1983), which show the importance of tonalitic and gabbric intrusions in elevating temperatures during early Tertiary granulite-facies metamorphism and anatexis.

The regional relations that constrain the interpretation of the tectonic setting for crustal melting in the Sanak-Baranof belt are listed below.

1. There is an apparent difference in age between the eastern (45 to 53 Ma) and western (58 to 60 Ma) segments of the belt.

2. The plutons postdate the deformation that accompanied accretion of the Upper Cretaceous and at least some of the Paleocene sedimentary and volcanic rocks in the Kodiak Island area and the Paleocene to early middle Eocene deformation of similar rocks in Prince William Sound and the eastern Chugach Mountains (Plafker and others, 1985). Mafic magmatism coeval with, or slightly older than, Sanak-Baranof granite emplacement, but also postdating accretionary deformation of Upper Cretaceous and Paleocene rocks, is recognized only locally in the eastern Prince William Sound area (G. Plafker, oral communication, 1986).

3. The plutons of the Sanak-Baranof belt postdate a major episode of subduction and are coeval with, and subparallel to, the Alaska Range–Talkeetna Mountains and Coast Mountains belts of crustally derived plutons (Fig. 7).

4. Paleogene high-grade metamorphism in the eastern Chugach Mountains may require a geothermal gradient of as much as 50°C/km at the time of metamorphism (Hudson and Plafker, 1982).

Three origins have been proposed to explain the plutons of the Sanak-Baranof belt: (1) reestablishment of geotherms within a thick accretionary prism upon slowdown or cessation of accretion (Hudson and others, 1979); (2) high heat flow associated with migration of a ridge-trench-trench triple junction along the continental margin (Marshak and Karig, 1977); and (3) high heat flow associated with emplacement of possibly ridge-related mafic magmas into the accretionary prism (Hill and others, 1981).

The second and third proposed origins are here considered unlikely because mafic magmatism, coeval with granitic plutonism and postdating accretionary deformation, is rare in the Gulf of Alaska region. Hill and others (1981), for example, argue that such mafic magmas explain some of the chemical and isotopic characteristics (e.g., $^{87}Sr/^{86}Sr_i$ and Sr content) of the Paleogene plutons in the western segment of the Sanak-Baranof belt. However, some of these compositional characteristics could be inherited from potential source rocks in the accretionary prism that include mafic volcanic assemblages along with the voluminous flysch sequences (e.g., Page and others, 1986).

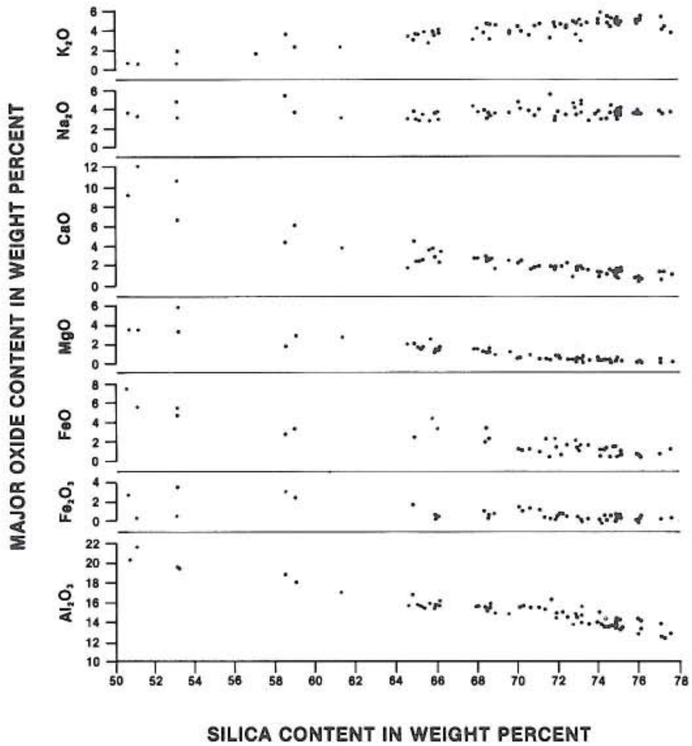

Figure 7. Variation of major oxides with silica for Paleogene granitic rocks in the Alaska Range–Talkeetna Mountains and Coast Mountains belts (*; does not include data for the tonalite of Skagway reported by Barker and others, 1986) and the Sanak-Baranof belt (●). See text for sources of data.

The origin of the Sanak-Baranof belt, though uncertain, is probably closely linked to plate-tectonic processes. One additional hypothesis consistent with the foregoing constraints is presented here. This hypothesis assumes that young, relatively hot oceanic lithosphere was being subducted along the Gulf of Alaska margin during the Late Cretaceous and earliest Tertiary. When subduction slowed, this hotter lithosphere would have come to rest beneath the continental margin, producing the higher heat flow required throughout the region for Paleogene anatexis in the already tectonically thickened accretionary prism. Somewhat longer subduction on the eastern limb than on the western limb of the belt then explains the apparent age differences between the two limbs. This hypothesis provides for elevated heat flow on a regional scale and is consistent with the field relations that led to the first of the three proposed origins listed for the Sanak-Baranof belt (Hudson and others, 1979; Hudson and Plafker, 1982).

DISCUSSION

The crustal melting events indicated by the nature and timing of granitic plutonism provide some important insights into the regional geology and tectonic framework of Alaska. The key insight into the regional geology comes from the recognition that similar Devonian crustal melts evolved in all of the more deeply exposed cratonic blocks of interior and northern Alaska; the Seward Peninsula, Brooks Range, Ruby geanticline, and the Yukon-Tanana Upland. The setting in which these melts developed appears to be one of extensional or wrench tectonics, an interpretation that is consistent with some recent suggestions by others working elsewhere along the western Paleozoic margin of North America (Eisbacher, 1983; Miller and others, 1984; K. Ehman, written communication, 1984; Plafker and Berg, this volume, Chapter 33). This interpretation, with its inferred correlation, requires that the major cratonic blocks of interior and northern Alaska be related to the continental margin of North America and not exotic fragments that have been transported from some distant origin in the ancient Pacific (Coney and others, 1980). This conclusion does not preclude significant differential translation of these crustal blocks along the continental margin itself.

If these cratonic blocks are related, even indirectly, to one another and to the North American continental margin in Devonian time, then their subsequent regional evolution is likely to have some similarities. Such similarities seem to be present in areas affected by the middle Mesozoic metamorphism, deformation, and plutonism outlined above, with one possible exception. The Brooks Range apparently lacks evidence of mid-Cretaceous granitic plutonism (Dillon and others, 1980) such as that on Seward Peninsula, the Ruby geanticline, and in the Yukon-Tanana Upland (Fig. 5), although the Brooks Range underwent similar episodes of a Late Jurassic or Early Cretaceous high pressure metamorphism, compressional deformation, and subsequent uplift. This distinction suggests that vertical displacements are an important factor in the regional tectonics of interior Alaska.

All the areas characterized by voluminous mid-Cretaceous granodiorite and granite plutonism are deeply eroded, relatively high-grade metamorphic regions that have been uplifted with respect to nearby areas. These deeply eroded regions include the youthful, fault-bounded Kigluaik, Bendeleben, and Darby Mountains on Seward Peninsula, the northern part of the Ruby geanticline relative to adjacent areas in the southern Brooks Range and its continuations south of the Kaltag fault, and such subdivisions of the Yukon-Tanana Upland as the crustal block between the Shaw Creek and Mt. Harper lineaments. These relations suggest that most of the mid-Cretaceous granitic magmas were emplaced at intermediate (mesozonal) crustal levels. If such levels are not widely exposed, even in the regions where melting occurred, significant granite and granodiorite plutons will not crop out. The Brooks Range, for example, is a major fold and thrust belt that is not as deeply eroded as adjacent areas characterized by abundant mid-Cretaceous granitic rocks. This lack of deep erosion may explain why such plutons are not exposed in the southern Brooks Range although they may be present at depth. Vertical displacement and subsequent erosion are therefore considered to be important factors controlling the present exposures of mid-Cretaceous, crustally derived plutons in interior Alaska.

CONCLUSION

This study represents an attempt to identify the timing and setting of major crustal melting events in Alaska. In order to do so, it has focused on granodiorite and granite plutons that can reasonably be inferred to have an origin dominated by crustal melting. There probably are other less obvious plutonic and related volcanic rocks that also have a crustal origin (e.g., parts of the widespread, early Tertiary magmatic province of interior Alaska?). Because granitic plutonism in subduction-related plutonic belts may be closely linked to deeper crustal processes as well as to mantle processes (e.g., Leeman, 1983), the simplifying distinction originally made in this study seems somewhat arbitrary. However, the results show that this distinction—focusing as it does on regional plutonism of granodiorite and granite composition—helps identify important temporal and spatial regional relations.

This analysis suggests that crustal melting was an important process in the evolution of Alaska during the Devonian, the Cretaceous, and the Paleogene and that four different regional tectonic settings characterize the recognized times of crustal melting. These are: (1) an extensional and/or wrench setting during the Devonian in which high heat flow resulted in melting, (2) a post-compressive deformation setting during the mid-Cretaceous in which uplift of thickened crust resulted in melting, (3) a post-magmatic arc setting during the Paleogene in which high heat flow associated with arc magmatism resulted in melting, and (4) a post-accretion setting during the Paleogene in which crustal thickening combined with high heat flow resulted in melting. These four settings emphasize the diversity of conditions that can lead to crustal melting in the North America Cordillera.

ADDENDUM (11/89)

Since this report was first written in 1984, the opportunity to revise and update it has come about several times. At these times, editorial and technical review provided viewpoints and feedback that helped formulate revisions. However, throughout these revisions, adherence to the original available data, concepts, and conclusions has been maintained in order to correctly record the chronology of this work.

Considerable other work has been accomplished in Alaska since 1984, some of which is especially relevant to the main focus of this chapter. In the author's opinion, the recent contributions that have the most impact on the concepts and conclusions of this report are those clarifying the role of extension in the Cretaceous history of interior Alaska and those constraining interpretations of the origins of the Sanak-Baronof plutonic belt.

As noted in the original report, the regional distribution of metamorphic and plutonic rocks alone suggests major vertical tectonic displacements in interior Alaska during the mid-Cretaceous. However, the first work to place these vertical displacements and other aspects of Alaska Cretaceous history into a comprehensive extensional framework was that of Miller (personal communication, 1985; 1987). This work, together with the recognition of specific regional normal faults on the south side of the Brooks Range (Box, 1987; Oldow and others, 1987; Moore and others, this volume) has just started to clarify the character and extent of this extensional tectonic regime, but it has very important implications for all of the mid-Cretaceous regional elements in Alaska. For example, one implication might be that mid-Cretaceous and Late Cretaceous magmatism of the Yukon-Koyukuk province (112 to 80 Ma), represents mantle and crustal melting that accompanied extension—the variety of highly potassic, felsic, and intermediate composition plutonism in this province would primarily reflect the variety of source regions that underwent melting at this time. In this context, the mid-Cretaceous granodiorite and granite of regions peripheral to the Yukon-Koyukuk province would have formed in a similar tectonic regime but in regions with more uniform continental crustal substrata. Regardless, extension in the Cretaceous evolution of Alaska seems to be increasingly supported by recent studies and has the potential to unify many perplexing aspects of the tectonic history of this important time. The developing extensional concepts for Alaska have not required modification of the original conclusions of this report but they have clearly expanded the scope of implications that conclusions concerning the origin of mid-Cretaceous granodiorite and granite plutonism have; continuing efforts to place Alaska Cretaceous tectonic elements into a unifying tectonic framework are clearly justified.

The second area of recent contributions that are especially relevant to this report are those that help to constrain the origins of the Sanak-Baranof plutonic belt. These contributions include a new synthesis of Late Cretaceous and early Tertiary magmatism in southern Alaska (Bergman and others, 1987), thermal modeling (James and others, 1989), and petrologic and geochronologic studies (Sisson and others, 1989) of the Chugach Metamorphic Complex. The Chugach Metamorphic Complex (Hudson and Plafker, 1982) is a window into deeper structural levels of the Late Cretaceous accretionary prism that developed along the Gulf of Alaska continental margin. Metamorphism and anatexis in the Chugach Metamorphic Complex are considered representative of at least the shallower crustal melting environments that were the source of the plutons of the Sanak-Baranof plutonic belt (Hudson and others, 1979; Hudson and Plafker, 1982). The relations in the Chugach Metamorphic Complex require high geothermal gradients (40 to 60°C per km; Sisson and others, 1989) at the time of metamorphism and melting. The origin of the heat flow required to develop these thermal gradients was a topic of some discussion at the time this report was first written.

This author has emphasized that field relations around the Gulf of Alaska margin do not indicate significant influx of mafic magmas into the accretionary prism at the time of anatexis. This has been taken by the author as evidence that ridge subduction (Marshak and Karig, 1977; Hill and others, 1981) is not the cause of early Tertiary high heat flow. One alternative cause originally put forth in this report, the emplacement of youthful and warm oceanic crust beneath the accretionary prism, was tested by the thermal modeling studies of James and others (1989). These workers showed that it was possible to produce the required high heat flow if the oceanic crust emplaced beneath the accretionary prism was very young, on the order of 1 Ma or less. The youthfulness that is required seems to make the distinction between warm oceanic crust and a ridge somewhat academic. Therefore, modification of this hypothesis is in order—especially in light of a conclusion reached by Bergman and others (1987) concerning the tectonic framework of Late Cretaceous and early Tertiary magmatism throughout southern Alaska.

Bergman and others (1987) have concluded that a significant change in the tectonic framework of southern Alaska took place at about 63 Ma. In summary, this change marked the shift from rapid convergence along a shallow-dipping subduction zone in the Late Cretaceous to slower convergence along a more steeply dipping subduction zone like that of today in the early Tertiary (Eocene?). This shift suggests two important early Tertiary events: (1) the cessation or slowdown of subduction (Hudson and others, 1979), and (2) a breaking and sinking of the down-going oceanic plate upon resumption of subduction. The breaking and sinking of the oceanic plate could develop a tectonic regime that would allow mantle material to be emplaced near or subjacent to the accretionary prism. This presents another possible cause of high heat flow along the Gulf of Alaska margin at exactly the time it is needed (Paleocene and early Eocene). This new interpretation for the cause of high heat flow needs further evaluation, but it is consistent with several regional geologic relations in southern Alaska.

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NOTES ADDED IN PROOF

Work accomplished since 1989 that is pertinent to this report includes studies in the Sanak-Baranof plutonic belt, amplification of the mid-Cretaceous regional extension model for interior Alaska, and continuing discussion of the origin of the Devonian orthogneisses. None of the new data or discussions have required significant changes in the original interpretations of this report.

Geochemical and isotopic data on Eocene granodiorite in the eastern Gulf of Alaska (Barker and others, 1992), support an origin by partial melting of the accretionary prism intruded by the Sanak-Baranof belt plutons. Isotopic data on the accretionary rocks themselves has been recently reported by Farmer and others (1993).

The early thoughts concerning the role of extension in the mid-Cretaceous tectonic evolution of interior Alaska, and therefore the setting in which voluminous crustally derived granodiorite and granite was emplaced, evolved in a report by Miller and Hudson (1991). This report links several key geologic relations of interior and northern Alaska in a model requiring large-scale crustal extension during the mid-Cretaceous. This model and many interpretations that support it are the source of continuing controversy (Till and others, 1993).

The origin of the Devonian orthogneisses is further constrained by some new isotopic data (Nelson and others, 1993). Nelson and others (1993) favor a continental-margin volcanic arc setting for the origin of these metaigneous rocks as have Rubin and others (1990) and Plafker and Berg (this volume, Chapter 33). As originally discussed in this report, the compositional character of the Devonian orthogneisses and of the metavolcanic rocks that may be contemporaneous with them in Alaska is thought by the author to more likely have formed in an extensional or transcurrent tectonic setting rather than in a continental-margin volcanic arc setting.

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