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Chapter 18

Latest Cretaceous and Cenozoic magmatism in mainland Alaska

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INTRODUCTION

Continental Alaska has been the site of widespread magmatism throughout much of the late Mesozoic and Cenozoic, but until recently, most of this magmatism was unrecognized due to the lack of modern geologic maps or isotopic age data for large tracts of Alaska. Although parts remain unmapped, progress in reconnaissance mapping and dating have enabled workers to identify major late Mesozoic and Cenozoic magmatic provinces outside the well-known Aleutian arc and to speculate as to their tectonic implications and origin (Wallace and Engebretson, 1984).

This chapter defines major Late Cretaceous and Cenozoic magmatic provinces in Alaska outside the Aleutian arc (Kay and Kay, this volume; Vallier and others, this volume; Miller and Richer, this volume) and southeast Alaska (Brew, this volume), and discusses their distribution, age, petrology, and tectonic implications. The available data suggest that Late Cretaceous and Cenozoic magmatism in continental Alaska can be roughly divided into three periods: (1) latest Cretaceous and early Tertiary (76 to 50 Ma), (2) middle Tertiary (43 to 37 Ma), and (3) late Tertiary and Quaternary (6 Ma to the present). Late Cretaceous and early Tertiary calc-alkalic volcanism and plutonism were widespread over much of western, central, and southern Alaska and on the Bering Sea shelf. Middle Tertiary magmatism was characterized by the eruption of small volumes of calcalkalic rocks in interior Alaska, contemporaneous with the inception of a major pulse of magmatism in the Aleutian arc. Late Tertiary and Quaternary volcanism has been characterized by the eruption of voluminous basaltic magma at numerous sites along the western margin of Alaska and on the Bering Sea shelf.

This chapter is accompanied by a map showing Cenozoic volcanic and plutonic rocks for the entire state at a scale of 1:2.5 million (Moll-Stalcup and others, this volume, Plate 5). Place names used in this chapter appear on that map. Although only major belts of regional significance are discussed in this chapter, tables summarizing age, lithologic, and chemical data for all the Latest Cretaceous to Quaternary volcanic and plutonic rocks outside the Aleutian arc and southeast Alaska are found on Plate 5.

Rock nomenclature used in this chapter generally follows that of Streckeisen (1979), Gill (1981), and Morrison (1980). On an anhydrous basis, basalts have less than 53 percent SiO_2, andesites have 53 to 63 percent SiO_2, dacites have 63 to 70 percent SiO_2, and rhyolites have more than 70 percent SiO_2. Fe_2O_3/FeO was set to 0.15 for the late Cenozoic basalts in order to calculate Mg numbers and normative mineralogies. The late Cenozoic rocks are classified as follows: Basalt having normative nepheline is called alkali basalt or alkali olivine basalt if it contains more than 10 percent normative olivine. Basalt having normative hypersthene is called tholeiite or olivine tholeiite if it contains more than 10 percent normative olivine. Basanites have 10 to 20 percent normative nepheline; nephelinites have more than 20 percent normative nepheline. Hawaiites have more than 5 percent total alkalies ($Na_2O + K_2O$) and less than 5 percent MgO. The Late Cretaceous, early Tertiary, and middle Tertiary suites are classified using the Peacock index and are then divided into low-, moderate-, or high-K, after Gill (1981), or shoshonitic after Morrison (1980). An upper limit for Fe_2O_3 was set by the formulate $\%Fe_2O_3 = \%TiO_2 + 1.5$ (after Irvine and Baragar, 1971). All ages were obtained by K/Ar methods unless otherwise noted.

All the Late Cretaceous and early Tertiary volcanic and plutonic rocks and some of the middle Tertiary rocks are hydrothermally altered and weathered, and I therefore have relied heavily on trace elements for interpretation of the geochemical data. Typical plutonic samples have about 1 percent total H_2O and 0.2 percent CO_2, and typical volcanic rocks have 1 to 4 percent H_2O^t and 0.2 percent CO_2. Pyroxenes and feldspars are generally fresh, but olivine, biotite, and hornblende are altered in some samples. Alteration of rocks from five volcanic fields, which are typical of much of the magmatic province, are described in more detail in Moll-Stalcup (1987). The late Cenozoic volcanic rocks are fresh, and even olivine is well preserved in most samples.

LATEST CRETACEOUS AND EARLY TERTIARY MAGMATISM

Latest Cretaceous and early Tertiary magmatic activity occurred in a vast region of Alaska stretching from the southern continental margin north to the Arctic Circle and west to the

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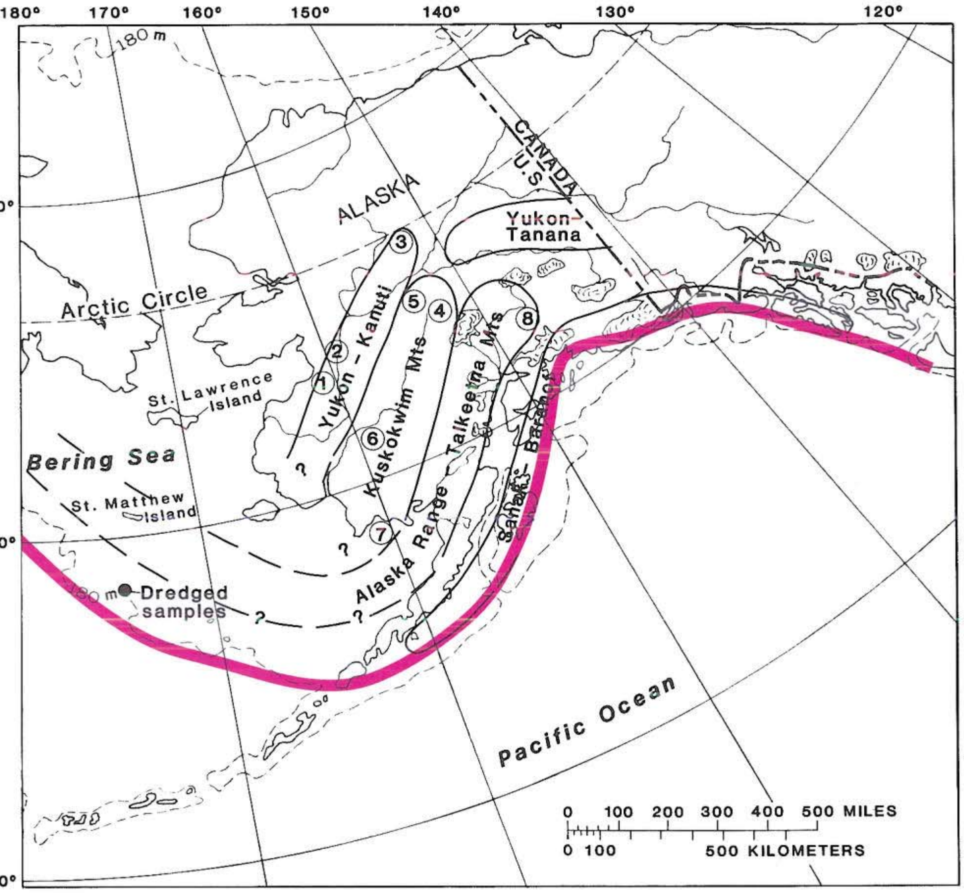


Figure 1. Location of Late Cretaceous and early Tertiary volcanic and plutonic belts of mainland Alaska. Proposed Paleocene continental margin shown in red. A few locations are: 1, Blackburn Hills volcanic field; 2, Yukon River area; 3, Kanuti volcanic field; 4, Sischu volcanic field; 5, Nowitna volcanic field; 6, Sleetmute area; 7, Bristol Bay; and 8, Talkeetna Montains. Dashed line marking 180-m water depth delineates edge of the Bering Sea shelf.

Bering Sea shelf (Fig. 1), possibly extending as far west as contemporaneous magmatic belts in eastern Siberia. Hudson (1979) and Wallace and Engebretson (1984) group the widespread volcanic and plutonic rocks in southern, western, and central Alaska into volcano-plutonic belts. From south to north, these are: The Sanak-Baranof belt, the Alaska Range–Talkeetna Mountains belt, and the Kuskokwim Mountains belt. An additional, previously unnamed, belt occurs farther to the northwest and is herein named the Yukon-Kanuti belt. Little-known volcanic and plutonic rocks of latest Cretaceous and early Tertiary age also occur in the Yukon-Tanana area of east-central Alaska (Foster and others, this volume), but their correlation and tectonic affinities are unknown. Data on the Late Cretaceous and early Tertiary rocks in the Yukon-Tanana upland are summarized on Table 1 of Plate 5, but those rocks are not discussed further in this chapter. The Sanak-Baranof belt, which consists of early Tertiary granitic plutons emplaced into the Gulf of Alaska accretionary wedge, extends along the southern margin of Alaska to Baranof Island in southeast Alaska and is described by Hudson (this volume).

Alaska Range–Talkeetna Mountains belt

The Alaska Range–Talkeetna Mountains belt consists of numerous coalescing plutons and subordinate volcanic rocks that extend in a broad belt, about 150 km wide, from the central Alaska Range, west and south to the Iliamna Lake region (Fig. 1). Most of the rocks occur south of the Denali fault, except for a few small bodies north of the fault near Farewell Lake and the Tonzona River (Reed and Nelson, 1980). Plutonic and volcanic rocks in the Alaska Range–Talkeetna Mountains belt intrude and overlie the Dillinger, Kahiltna, and Peninsular terranes, as well as a number of smaller terranes in the Mt. McKinley area (Silberling and others, this volume). Aeromagnetic anomalies on the Bering Sea shelf (Godson, 1984; Cooper and others, 1986) and the presence of compositionally similar contemporaneous volcanic rocks on St. Matthew Island (Patton and others, 1975) suggest that the belt may continue southwest of Iliamna Lake under Bristol Bay, curving west and north along the submerged continental shelf of Alaska (Fig. 1).

Plutonic activity in the Alaska Range–Talkeetna Mountains belt is divided into an early stage (75 to 60 Ma), which occurred chiefly on the south-southeast flank of the belt; and a late stage (65 to 50 Ma), which occurred chiefly on the north-northwest flank of the belt. The early stage consists of dominantly intermediate to felsic plutons and includes many of the rocks of Summit Lake (Reed and Lanphere, 1972), the Mount Susitna pluton (Magoon and others, 1976), and a large tonalite pluton in the southern Talkeetna Mountains (Csejtey, 1974). The late stage consists generally of felsic plutons and includes the quartz monzonite of Tired Pup, the Crystal Creek sequence, the McKinley sequence (Reed and Lanphere, 1972), and numerous granitic plutons in the northern Talkeetna Mountains and the adjacent southern Alaska Range (Csejtey and others, 1978, 1986).

Volcanic rocks in the Talkeetna Mountains consist of several small fields and one large field approximately 90 by 25 km that trends southeast perpendicular to the belt. The large volcanic field is more than 1,500 m thick and is composed of rhyolite and dacite stocks, irregular dikes, lenticular flows, and thick pyroclastic rocks at the base grading up into gently dipping interlayered basalt and andesite flows at the top (Csejtey and others, 1978). Three rocks from about midsection give ages of 56.5 to 50.4 Ma, indicating that the lower part of the section is Paleocene and Eocene in age. The stratigraphically high mafic and intermediate flows are thought to be equivalent in age to Miocene lava flows in the Wrangell Mountains (Csejtey and others, 1978).

The volcanic rocks of the Cantwell Formation crop out north of the Talkeetna Mountains volcanic rocks in the central Alaska Range, covering about 165 km^2 in the eastern part of the Mount McKinley National Park. They consist of at least 3,750 m of mostly andesite and rhyolite flows and subordinate basalt flows, felsic pyroclastic rocks, and related intrusive rocks (Gilbert and others, 1976). Gilbert and others (1976) considered the K/Ar ages of 60.6, 57.2, and 41.8 Ma to be minimum ages and interpret the formation as Paleocene in age.

Little-known volcanic rocks near Lake Clark consist of undivided Paleocene and Eocene volcanic and associated plutonic rocks that crop out discontinuously over more than 3,000 km^2 in the area between Lake Clark and the Mulchatna River (Nelson and others, 1983). The volcanic rocks are 62.7 to 56.2 Ma (Eakin and others, 1978) and 44.4 to 39.7 Ma (Thrupp and Coe, 1986); adjacent shallow plutons are 71.3 to 60.5 Ma (Nelson and others, 1983). The volcanic rocks are described as rhyolite breccia, lava flows and ash-flow tuffs, and subordinate mafic to intermediate flows; the intrusive rocks are described as granite, granodiorite, and diorite (Nelson and others, 1983).

The east Susitna batholith (Plate 5) occurs at the east end of the Alaska Range–Talkeetna Mountains belt on the east limb of the bend in the Denali fault. Although the batholith yields Late Cretaceous and early Tertiary minimum ages, it is not considered to be part of the Alaska Range–Talkeetna Mountains belt because it consists of regionally metamorphosed and penetratively deformed diorite, granodiorite, and quartz monzonite that give a wide range of K/Ar ages (Nokleberg and others, 1982; Table 1 on Plate 5), and because it is thought to have been 400 km from its present position at the time of its emplacement (Nokleberg and others, 1985). Tertiary displacements on regional strike-slip faults along the east side of the bend in the Denali fault, where the east Susitna batholith occurs, are thought to be much greater than displacements on the west side, where most of the Alaska Range–Talkeetna Mountains belt occurs. Because the batholith probably is allochthonous relative to the Alaska Range–Talkeetna Mountains belt and thus is not part of this belt, and because its age is ambiguous, it is not discussed further in this chapter.

Petrogenesis. The calc-alkalic plutons and volcanic rocks in the Alaska Range–Talkeetna Mountains belt are typical of continental-margin arc rocks, and are characterized chemically by low TiO_2, moderate K_2O and lack of Fe-enrichment (data from Reed and Lanphere, 1972, 1974a; Csejtey, 1974; Csejtey and others, 1978; Gilbert and others, 1976; Lanphere and Reed, 1985). The early-stage plutons in the Alaska Range are dominantly intermediate to felsic (54.5 to 70 percent SiO_2) and are compositionally equivalent to medium-K orogenic andesites and dacites. Plots of SiO_2 versus Na_2O and Ca-Na-K distinguish two suites of rocks: a diorite, tonalite, trondhjemite suite similar to the calc-alkalic-trondhjemite suite of southwest Finland (Arth and others, 1978) and a "normal" calc-alkalic suite. I was not able to determine from the published data (above references) whether the two suites are temporally or geographically distinct.

The late-stage plutons in the Alaska Range are generally more felsic and are divided into two groups on the basis of mineralogy and chemistry. One group is a normal calc-alkalic suite similar to the early-stage plutons and consists of the early Tertiary Crystal Creek pluton and numerous small granitic bodies in the northern Alaska Range. The other group is represented by the McKinley sequence and the quartz monzonite of Tired Pup (Lanphere and Reed, 1985; M. A. Lanphere, personal communication, 1984), which consist of siliceous peraluminous granites that plot at minimum-melt compositions on a Q-Ab-Or diagram and have moderately high strontium initial ratios ($^{87}Sr/^{86}Sr$ = 0.7054 to 0.7085; Lanphere and Reed, 1985). Lanphere and Reed (1985) interpret the chemical and isotopic data of the McKinley sequence as the result of mixing of mantle-derived magmas with upper Mesozoic flysch into which the plutons were intruded. They believe that this mixing took place in the early Tertiary during the collision between stable Alaska and southern accreted terranes. Paleomagnetic data, however, suggest that the terranes were accreted by Late Cretaceous time (Hillhouse and Coe, this volume). K/Ar ages (Lanphere and Reed, 1985; Reed and Lanphere, 1972, 1974a) suggest that these plutons were emplaced at the end of a long period of arc magmatism and that they may simply mark the end of this event. Chondrite-normalized multi-element diagrams for the McKinley sequence show large depletions in Nb and Ta, which are diagnostic of arc magmatism (Fig. 2; Perfit and others, 1980; Gill, 1981; Thompson and others, 1984).

Volcanic rocks having ages between 58 and 50 Ma crop out in the northern Alaska Range and Talkeetna Mountains at the east end of the belt. Limited petrologic data on the lower se-

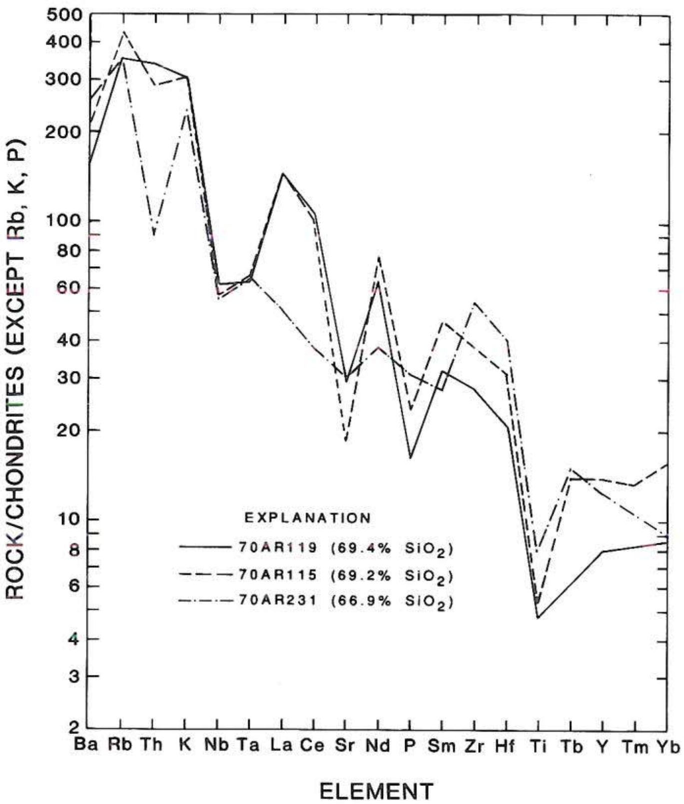


Figure 2. Chondrite-normalized spidergrams for rocks from the McKinley sequence. Data from Lanphere and Reed (1985); normalization factors from Thompson and others (1984). The rocks have deep Nb-Ta troughs characteristic of subduction- related magmas. Sharp spikes at Sr, P, and Ti suggest that the rocks are highly differentiated and have fractionated plagioclase, Fe-Ti oxides, and apatite.

quence of the Talkeetna Mountains volcanic rocks suggest they are typical of orogenic belts and are similar in composition to the older Summit Lake plutons. Analyzed rock samples from the Cantwell Formation have higher TiO_2 and lower Al_2O_3 (Gilbert and others, 1976)—both immobile elements—than the other clearly orogenic suites. Granitic plutons in the same region also have ages from 58 to 50 Ma, but their affinities are not known. The lack of muscovite and presence of rare hornblende suggest that they are similar to the Crystal Creek sequence, but the association of some plutons with tin mineralization suggests instead that they may be correlative with the peraluminous McKinley sequence.

The age and composition of the Talkeetna Mountains volcanic rocks suggest that arc volcanism occurred later in the eastern part of the belt than in the western or southern parts. Arc volcanism appears to have migrated gradually north between about 65 and 58 Ma, then east, until it shut off at about 50 Ma.

Kuskokwim Mountains belt

The Kuskokwim Mountains belt is a Late Cretaceous and early Tertiary volcanic-plutonic belt that extends along the entire length of the Kuskokwim Mountains for more than 800 km, from Bristol Bay to about latitude 64° (Fig. 1). Studies in the Medfra Quadrangle (Patton and others, 1980; Moll and others, 1981), in the Iditarod and McGrath Quadrangles (M. L. Miller, personal communication, 1986; Bundtzen and Laird, 1982, 1983a, b, c), in the Sleetmute Quadrangle area (Robinson and others, 1984; Decker and others, 1984, 1985, 1986; Reifenstuhl and others, 1984, 1985), and in the Tikchik Lakes–Bristol Bay region (Hoare and Coonrad, 1978b; Wilson, 1977; Globerman, 1985) have led to the recognition of this volcanic and plutonic belt of Late Cretaceous and early Tertiary age (Moll and Patton, 1982; Wallace and Engebretson, 1984). Compilation of more than 90 K/Ar ages from volcanic and plutonic rocks along the belt (E. J. Moll, unpublished data, 1985) suggests that the main magmatic pulse occurred between 72 and 60 Ma, contemporaneous with the older-stage plutonism in the Alaska Range. It is not yet clear if the Kuskokwim Mountains belt is separate from the Alaska Range–Talkeetna Mountains belt. Much of the area separating the two belts is covered by Quaternary surficial deposits on the north side of the Farewell fault and in the vicinity of the Mulchatna fault. Exposures of plutonic and volcanic rocks in low hills in the Farewell Lake area and on both sides of the Mulchatna fault suggest that the two belts may be continuous. The volcanic and intrusive rocks in the Kuskokwim Mountains belt are divided into six groups: (1) northern volcanic fields; (2) northern volcanoplutonic complexes; (3) northern plutons, dikes, and sills; (4) volcanic and plutonic rocks in the Sleetmute-Nyac area; (5) plutonic rocks of the southern Kuskokwim Mountains region; and (6) the Bristol Bay volcanic sequence. The northern part of the belt overlies the Ruby, Innoko, Nixon Fork, and Minchumina terranes; the southern part overlies the Dillinger, Tikchik Lake, Nyac, Kilbuck, Togiak, and Goodnews terranes of Jones and others (1987), and Silberling and others (this volume).

The northern volcanic fields include the Sischu, Nowitna, Dishna, and Yetna volcanic fields (Fig. 1; Plate 5). The Sischu volcanic field (71 to 66 Ma) consists of a narrow belt of poorly exposed rhyolite and dacite domes, flows, and tuff that extends from the Sischu Mountains to the southern Chitanatala Mountains (Moll and others, 1981; Moll-Stalcup and Arth, 1989). The main volcanic field covers an area of more than 725 km^2, is at least 500 m thick, and is fault bounded on the southeast side. A felsic pluton that crops out just east of the volcanic rocks has an age of 64 Ma (Silberman and others, 1979).

The Nowitna volcanic field consists of more than 1,500 m of chiefly andesitic flows preserved in a gently folded northeast-trending syncline that is fault-bounded on the southeast side. The field covers more than 2,700 km^2, overlapping the suture between the Innoko and Nixon Fork terranes. At least seven highly altered rhyolite domes overlie the andesite flows. K/Ar ages on three whole-rock andesite samples collected near the top of the section are 64 to 63 Ma (Silberman and others, 1979).

The Dishna volcanic field consists of calc-alkalic dacite, rhyolite, and minor andesite poorly exposed in a series of isolated ridges and hills that rise above the alluvium in the Innoko-Dishna

Rivers area (Chapman and others, 1985). These undated rocks are presumed to be Late Cretaceous or early Tertiary in age.

Volcanoplutonic complexes occur in the McGrath area at Page Mountain, Cloudy Mountain, Candle Mountain, Takotna Mountain, Mount Joaquin, the Beaver Mountains, and in the Lonesome Hills. These complexes have circular-shaped outcrop areas that consist of andesite flows and shallow hypabyssal rocks intruded by small granitic stocks. Most of the volcanic rocks are highly altered by the intrusions. The margins of many of the complexes appear to be fault-bounded and the complex at Page Mountain is down-faulted against the surrounding sedimentary rocks. The complexes are interpreted as being deeply eroded volcanic centers. Dates on volcanic and intrusive rocks from these complexes yield K/Ar ages ranging from 73 to 65 Ma (Moll and others, 1981; Bundtzen, and Laird, 1982, 1983a, b, c).

Widespread intrusive rocks, many too small to be shown on published maps, occur throughout the Kuskokwim Mountains belt. In the northern Kuskokwim Mountains, numerous dikes, sills, and small stocks, usually 1 to 9 km in diameter, give similar K/Ar ages (72 to 62 Ma) and are compositionally similar to the volcanic rocks. Most of the intrusive rocks are compositionally homogeneous monzonite, monzodiorite, quartz monzodiorite, quartz monzonite, or granite. Plutons at Von Frank and Stone Mountain, however, are compositionally zoned, and commonly grade inward from gabbro or monzogabbro at the margin, to quartz monzonite in the center of the pluton.

Volcanic and plutonic rocks in the Sleetmute-Nyac area have K/Ar ages ranging from 75 to 61.7 Ma (Robinson and others, 1984; Decker and others, 1985, 1986; Reifenstuhl and others, 1984). The volcanic sequence, named the Holokuk Basalt by Cady and others (1955), consists in fact of more than 1,000 m of chiefly andesite flows and lahars and minor rhyolite vitric tuff and breccia (Decker and others, 1986). Most of the andesites are older (74.5 to 64.3 Ma) than the rhyolites. Intrusive rocks include the Chuilnuk and Kiokluk granodiorite plutons dated at 68.7 to 67.5 Ma, intermediate stocks and dikes dated at 69.8 Ma, and a number of small rhyolite porphyries dated at 70.5 to 67.9 Ma and 61.5 Ma. Similar biotite and biotite-muscovite rhyolite porphyries occur to the north along the Nixon Fork–Iditarod fault and contain garnet (Bundtzen and Swanson, 1984).

More than 30 plutons, usually small stocks 3 to 15 km in diameter, occur in the southern Kuskokwim Mountains in the area between the Nushagak and Kuskokwim Rivers (Wilson, 1977; Hoare and Coonrad, 1978b). Hoare and Coonrad (1978b) describe them as monzonite, granodiorite, and quartz diorite stocks, "mafic" dikes and sills; and felsic dikes, sills, tuffs, and breccias. K/Ar ages for all the rock types in the Goodnews-Hagemeister Quadrangles range from 72.5 to 60.7 Ma. Poorly known granitic stocks to the north and east of the Goodnews-Hagemeister Quadrangles appear to be contemporaneous with, and compositionally similar to, those in the quadrangle (Wilson, 1977; J. M. Hoare, oral communication, 1980).

A thick sequence of volcanic rocks called the Bristol Bay volcanic sequence (Globerman, 1985) is exposed on Hagemeister, Walrus, and Summit Islands in Bristol Bay and on the adjacent mainland. The rocks are dated at 68.7 to 64.5 Ma (Globerman, 1985; Box, 1985). The volcanic rocks consist of andesitic lava flows interbedded with tuffs, breccias, and volcanogenic sedimentary rocks that are exposed in a section more than 2 km thick.

Petrogenesis. The Kuskokwim Mountains belt consists of moderate-K calc-alkalic to shoshonitic suites that range in composition from basalt to rhyolite. Present exposures suggest that andesite, followed by rhyolite, are the overwhelmingly dominant volcanic rocks types. Dacite and basalt are relatively uncommon, and rocks having less than 52 percent SiO_2 are rare. Most of the intrusive rocks have intermediate to felsic compositions, and many are compositionally equivalent to dacites, plotting in the silica gap (63 to 70 percent SiO_2) defined by the volcanic rocks. Mineralogies vary considerably according to rock type and K_2O content (Table 1, Moll-Stalcup and others, this volume).

Major-element data on the volcanic and plutonic rocks show trends typical of most igneous calc-alkalic suites: MgO, FeO*, TiO_2, Al_2O_3, and CaO decrease with increasing SiO_2; K_2O and Na_2O increase with increasing SiO_2. TiO_2 is low (less than 1.75 percent), and Al_2O_3 is moderate (12 to 17 percent). None of the suites shows Fe enrichment. K_2O varies from moderate (1.3 percent at 56 percent SiO_2) to very high values (4 percent at 56 percent SiO_2). Moderate to high-K suites plot in the subalkaline field of Irvine and Baragar (1971) on a total alkalies versus SiO_2 diagram and are calc-alkalic. Very high-K suites (Von Frank and Whirlwind on Fig. 3) plot in the alkalic field and are classified as shoshonitic (Morrison, 1980). Shoshonitic and calc-alkalic suites are similar in all major elements except K and P, which correlates with K. In the northern Kuskokwim Mountains the high-K calc-alkalic and shoshonitic suites tend to be older (71 to 65 Ma) than the moderate-K suites (68 to 62 Ma), although there is considerable overlap.

Major- and trace-element data suggest that the volcanic and plutonic rocks are highly enriched in Ba, Rb, Th, K, and Sr and depleted in Nb and Ta relative to La (Fig. 4). These features are characteristic of subduction-related arc rocks (Perfit and others, 1980; Gill, 1981; Thompson and others, 1984). All the rocks are LREE (light rare earth element) enriched, but the degree of enrichment varies, correlating with the abundance of K and other incompatible elements: shoshonitic rocks have La about 150; high-K rocks have La about 100; and moderate-K rocks have La about 75 × chondritic abundances. In contrast, andesites from the entire belt have similar HREE (heavy rare earth element) contents (6 to 13 × chondrites). There is also a rough correlation between geographic area and degree of incompatible-element enrichment. Andesites from the Bristol Bay volcanic sequence in the southernmost part of the belt have lower incompatible-element contents than andesites from Sleetmute, 360 km to the north (Table 1), which have lower incompatible-element contents than andesites and intermediate plutonic rocks from the northern Kuskokwim Mountains. LIL (large ion litho-

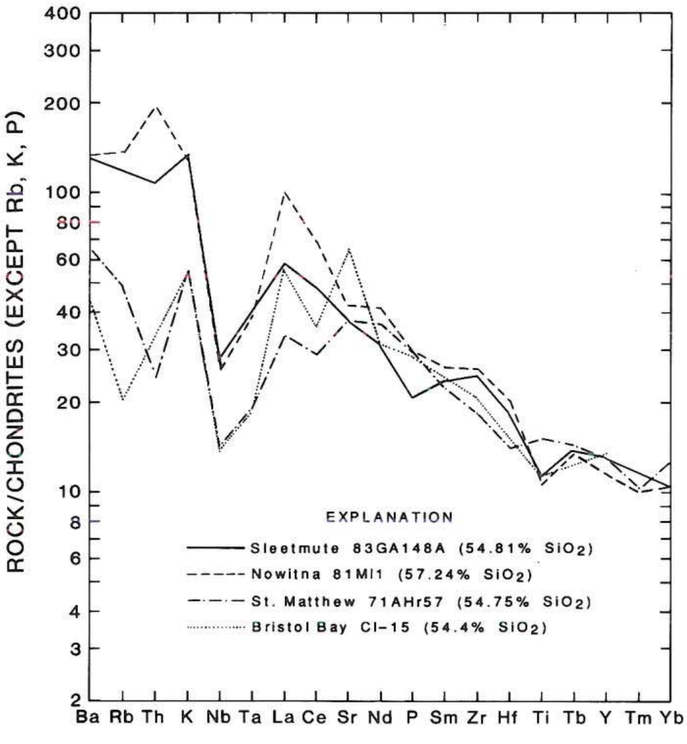


Figure 3. Chondrite-normalized spidergrams for andesites from the Kuskokwim Mountains belt and St. Matthew Island. Data for northern Kuskokwim Mountains (Nowitna) and St. Matthew Island from E. J. Moll-Stalcup and W. W. Patton Jr. (unpublished data, 1985). Data for Sleetmute from Decker and others (1986); for Bristol Bay from Globerman (1985).

phile) elements (K, Rb, Ba, Th, LREE) show the greatest increase from south to north; high-field-strength (HFS) elements (Zr, Hf, Nb, and Ta), which are also incompatible, increase to a lesser degree (Table 1). Alkali element contents in the highly altered volcanoplutonic complexes are high and variable, but REE data from the complexes are similar to data from the less altered Nowitna volcanic field, suggesting that the two suites are chemically similar (compare Cloudy Mountain and Nowitna on Fig. 5D). Trace-element ratios (Ba/Ta, Ba/La, La/Nb) in andesites from all three K-groups are similar to arc andesites (Gill, 1981) despite the higher contents of these elements in the high-K calc-alkalic and shoshonitic groups that are "typical" in arcs.

REE patterns for rhyolites, dacites, quartz monzonites, and granites from the Kuskokwim Mountains belt are highly variable. Most of the rhyolites and dacites from the Sischu volcanic field have patterns that have very high LREE and low HREE (3 to 5 × chondrites), but some have extremely high LREE and moderate HREE (Figs. 4A and 4B). The samples with low HREE contents show a weak correlation between silica and decreasing HREE, which Moll-Stalcup and Arth (1989) attribute to hornblende fractionation or formation by partial melting of a hornblende-bearing source (Moll-Stalcup, 1987). Rhyolites from the Sischu field that have extremely high LREE and very large negative Eu anomalies are probably highly fractionated high-silica rhyolites. Rhyolites and granites from the Sleetmute area have more moderate REE patterns (Fig. 4C) similar to those of the granitic intrusive rocks in the northern Kuskokwim Mountains.

Even the most mafic rocks in the Kuskokwim Mountains belt have compositions that suggest that they have undergone significant fractionation, and many show evidence for interaction with continental crust. In the northern Kuskokwim Mountains, where the basement is Precambrian and Paleozoic rocks, andesites from the Nowitna volcanic field have isotopic and trace-element variations that are best explained as assimilation of small amounts of continental crust during crystal fractionation (Moll and Arth, 1985; Moll-Stalcup and Arth, 1989). Rhyolites from the nearby Sischu volcanic field have high Sn, Be, U, W, and F contents and initial $^{87}Sr/^{86}Sr$ greater than 0.7080 (Moll and Arth, 1985; Moll and Patton, 1983), which suggests that they either were strongly contaminated by continental crust or were generated by partial melting of the crust.

In the Sleetmute area, initial $^{87}Sr/^{86}Sr$ varies from 0.704 to 0.706 (M. Robinson and R. Reifenstuhl, written communication, 1985). Initial $^{87}Sr/^{86}Sr$ does not correlate with SiO_2, Rb/Sr, or 1/Sr, indicating that crustal contamination of isotopically homogeneous magmas is not the only cause of this isotopic variation. Andesites, rhyolites, granites, and quartz monzonites have a similar range of initial $^{87}Sr/^{86}Sr$ (andesites: 0.7040 to 0.7060; felsic rocks: 0.7049 to 0.7063; M. Robinson and R. Reifen stuhl, written communication, 1985). The volcanic and plutonic rocks overlie sedimentary rocks of the Cretaceous Kuskokwim Group, but the nature and age of the older basement rocks is uncertain (S. Box, oral communication, 1986). The presence of andesites having initial $^{87}Sr/^{86}Sr$ as high as 0.706 suggests that old (Precambrian and Paleozoic) radiogenic continental crust or lithosphere, or sedimentary rocks derived from old continental crust occur in the Sleetmute area, although the mechanism for interaction with the crust is not yet understood. In contrast, initial $^{87}Sr/^{86}Sr$ on andesites from the Bristol Bay volcanic sequence are uniformly low (0.7037 to 0.7041; Globerman, 1985), indicating that old continental crust does not underlie this area.

St. Matthew Island, on the Bering Sea shelf, is composed entirely of Late Cretaceous and early Tertiary volcanic rocks ranging in composition from basalt to rhyolite (Patton and others, 1975). The island may be part of the Alaska Range–Talkeetna Mountains belt, part of the Kuskokwim Mountains belt, or neither, but the K_2O contents are most like those in volcanic rocks in the Alaska Range–Talkeetna Mountain belt (Fig. 5). No trace-element data on rocks from Alaska Range–Talkeetna Mountains belts have been published except for those on the anomalous McKinley sequence. Comparisons of incompatible-element contents between rocks from the Kuskokwim Mountains belt (Table 1) and rocks from St. Matthew Island show that the St. Matthew Island rocks have slightly lower abundances of incompatible elements than the Bristol Bay volcanic sequence, which has the lowest contents in the belt. REE data for St. Matthew andesites have lower LREE than andesites from either Sleetmute or the northern Kuskokwim Mountains (Fig. 4D), but have La contents similar to that of the Bristol Bay volcanic sequence (Table 1).

The unusually large range in incompatible element contents of rocks in the Kuskokwim Mountains belt is not well understood. K and incompatible elements vary geographically and temporally; along the strike of the belt, K increases from south to north, and in the northern Kuskokwim Mountains, the K content decreases with time from shoshonitic to moderate-K.

The volcanic and plutonic rocks in the Kuskokwim Mountains belt are compositionally similar to arc volcanic rocks that are thought to be generated by partial melting in a mantle wedge that has been modified by alkali-enriched fluids derived from the subducted slab and/or subducted sediments (Arculus and Powell, 1986). In arc magmas, K contents are separately influenced by the composition of the crust and the depth to the slab. K has been empirically observed to increase with distance from the trench, or depth to the slab. Additional factors that can influence the degree of K and other incompatible-element enrichment include greater degrees of crustal contamination or the presence of old, thicker, or more enriched crust or lithosphere. Estimates of crustal thickness from gravity studies (Barnes, 1977) suggest that the present crust is 30 to 35 km thick under the Kuskokwim Mountains, except in the southernmost part near Bristol Bay where it is 25 to 30 km thick. However, these present-day estimates are not well constrained because of the lack of seismic refraction data for the entire region. Furthermore, present-day crustal thickness may not be the same as crustal thicknesses in the early Tertiary.

The basement in the northern Kuskokwim Mountains consists of Precambrian and Paleozoic continental crust of the Ruby, Nixon Fork, and Minchumina terranes, which contrasts sharply with the late Paleozoic and Mesozoic mafic and intermediate oceanic rocks of the terranes in the south. Isotopic data suggest that the igneous rocks in the northern part of the belt have interacted with old continental crust. Thus, the increase in incompatible-element contents from south to north along the belt is probably related to the presence of old continental crust in the northern Kuskokwim Mountains.

Increasing incompatible-element contents along the strike of a continental arc has been documented by Hildreth and Moorbath (1988) in the Chilean Andes. They attribute the increase in incompatible elements from south to north to continental influence, because other factors, such as sediment subduction or depth to the Benioff zone, do not vary geographically, and the basement in the north is both thicker and older than the basement in the south.

K variation in rocks emplaced through old continental crust in the northern Kuskokwim Mountains cannot be attributed solely to the type of crust because all three suites overlie the same type of basement. Furthermore, there is no correlation between initial $^{87}Sr/^{86}Sr$ and K-type (E. J. Moll and M. L. Silberman, unpublished data, 1985), which suggests that the high K contents are neither the result of greater degrees of crustal contamination nor of local crustal inhomogeneities. There is, however, a weak correlation between age and K type, because the shoshonitic to high-K suites tend to be older than the moderate- to high-K suites. Perhaps the variation in K in the northern Kuskokwim Mountains is tectonically controlled by depth to the Benioff zone and the dip of the slab may have become shallower over time. This model would account for both the higher K content of the rocks and the occurrence of a narrower magmatic belt prior to 65 Ma. Alternatively, the older rocks may be more enriched in incompatible elements simply because those elements were concentrated in the first partial melts.

Yukon-Kanuti belt

The Yukon-Kanuti belt (Fig. 1) consists of an aligned group of early Tertiary volcanic fields that form a northeast-trending belt located north and west of the Kuskokwim Mountains belt. The belt extends from the Arctic Circle near the town of Bettles for more than 300 km southwest to the Kaltag fault and continues south of the fault on the west side of the Yukon River (Plate 5, Fig. 5). There is no clear boundary between the Kuskokwim Mountains and Yukon-Kanuti belts in the region south of the Kaltag fault. Late Cretaceous and early Tertiary volcanic rocks are divided into the two belts because the Yukon-Kanuti belt contains generally younger rocks (66 to 47 Ma) than are found in the Kuskokwim Mountains belt (76 to 60 Ma), and because the Yukon-Kanuti belt lies within the Yukon-Koyukuk province (Patton and others, this volume, chapter 7). The Yukon-Koyukuk province consists chiefly of late Paleozoic and Mesozoic mafic and intermediate volcanic rocks and associated sedimentary rocks, which contrast sharply with the Precambrian and lower Paleozoic schist and carbonate rocks that underlie the northern Kuskokwim Mountains belt. A further distinction is that the depth of post–early Tertiary erosion in the Yukon-Koyukuk province is shallower; as a result, there are more volcanic rocks and fewer plutonic rocks exposed in the Yukon-Kanuti belt than in the Kuskokwim Mountains belt.

Three areas in the Yukon-Kanuti belt have been studied in detail: The Kanuti volcanic field in the northern part, the Yukon River area located south of the Kaltag fault, and the Blackburn Hills volcanic field about 50 km farther southwest (Moll-Stalcup and Arth, 1989). Numerous small volcanic bodies, plutons, dikes, and sills, having K/Ar ages chiefly between 65 and 53 Ma, occur in the northern and central parts of the belt. Extensive volcanic and plutonic rocks of Tertiary age are shown on the geologic map of Alaska farther south (Beikman, 1974), but no detailed map, age, or petrologic data are available.

The Kanuti field lies within the Yukon-Koyukuk province near its southeast margin (Fig. 1). The field consists of dacite, andesite, and rhyodacite flows, domes, and tuffs exposed in a broad syncline that trends northeast and covers an area of more than 550 km^2. The base of the volcanic section is dated at 59.5 and 59.7 Ma, and the top at 55.9 Ma (Patton and Miller, 1973; Moll-Stalcup and Arth, 1989).

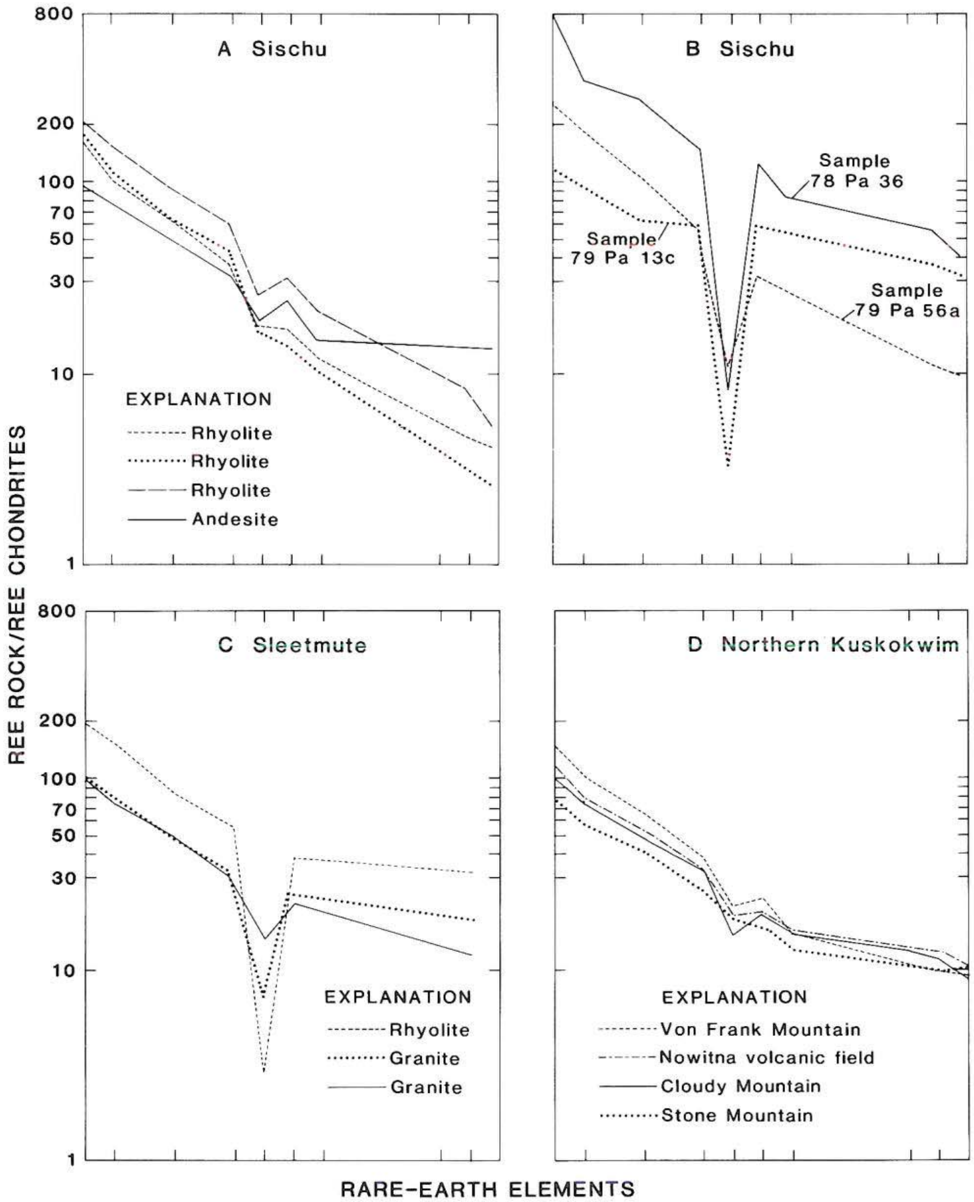
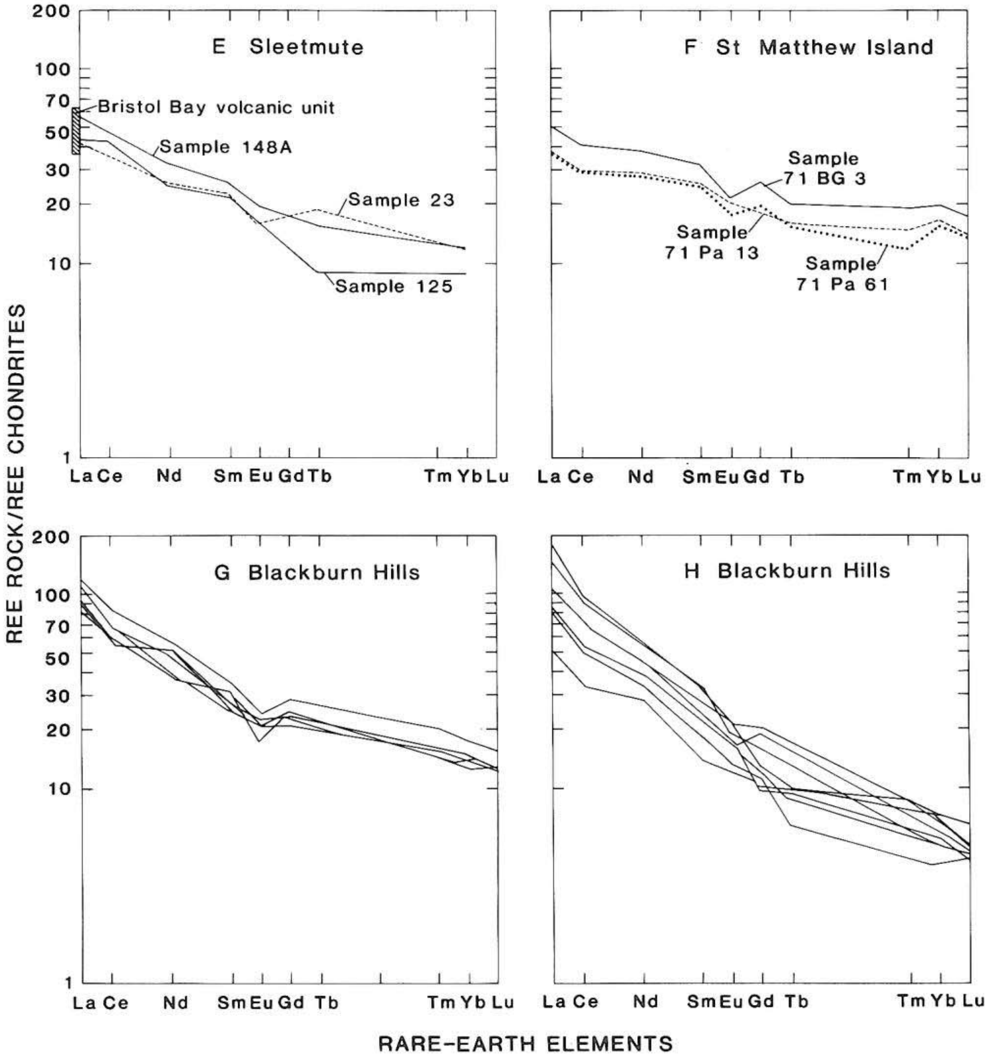


Figure 4. Eight chondrite-normalized rare-earth-element diagrams for rocks from five areas. A, andesite and rhyolites from the Sischu volcanic field having low HREE, which probably indicates hornblende or garnet fractionation. B, patterns for highly fractionated (high silica?) rhyolites from the Sischu volcanic field. C, rhyolite and granites from the Sleetmute area. D, REE data for andesites from the northern Kuskokwim Mountains: Von Frank = high K to shoshonitic; Nowitna = moderate to high K; Stone Mountain = moderate K; Cloudy Mountain = highly altered, but are thought to be shoshonitic on the basis of K_2O content. However, REE data suggest the Cloudy Mountain andesite may actually have moderate K contents. E, REE data for Sleetmute andesites. Chondrite-normalized La values for andesites of the Bristol Bay volcanic unit shown by a bar at La. F, REE data for andesites from St. Matthew Island. These rocks have very low K, Rb, Th, and LREE and may be correlative with the Alaska Range–Talkeetna Mountains belt for which we have no REE data. G and H, REE data for the Blackburn Hills volcanic field, showing the two andesite types that are distinguished on the basis of HREE: G, group 1 pyroxene andesites; H, group 2 pyroxene and hornblende andesites. Data for Sleetmute from Decker and others (1986); for Bristol Bay from Globerman (1985). All other data from E. J. Moll-Stalcup and W. W. Patton, Jr. (unpublished data, 1979–1986).



The Tokatjikh volcanic field, located about 75 km southwest of the Kanuti field near Tokatjikh Creek (Patton and others, 1978), consists of 275 km^2 of andesite and dacite flows and tuffs petrologically similar to those in the Kanuti field. A date of 59.6 ± 0.6 Ma on hornblende (W. W. Patton, Jr., written communication, 1989) indicates that the two fields are contemporaneous.

Another small volcanic field, located to the west, just south of the village of Huslia, near Roundabout Mountain, is undated and described as andesitic (Patton, 1966; Table 1, Moll-Stalcup and others, this volume). It is probably part of the early Tertiary volcanic belt, although it could be part of the younger mid-Tertiary (40 Ma) province discussed below.

Isolated domes, cones, and flows and one large volcanic field crop out in the dense vegetation along the west banks of the Yukon River south of the village of Kaltag (number 2 on Fig. 1). These rocks are the youngest volcanic rocks (53 to 47 Ma) in the Late Cretaceous and early Tertiary province of western Alaska and occur in three main locations. From north to south they are: (1) a large (400 km^2), poorly exposed volcanic field near Poisen Creek and Stink Creek that consists of basalt, andesite, dacite, and rhyolite (50.6 and 47.6 Ma, W. W. Patton, Jr. and E. J. Moll, unpublished data, 1981); (2) a large composite rhyolite dome and associated olivine basalt and pyroxene andesite flows at Eagle Slide (53.2 Ma, Patton and Moll, 1985); and (3) a morphologicaly well-preserved andesite cone located 6 km west of Bullfrog Island (53.8 Ma; Patton and Moll, 1985). Harris (1985) reports similar K-Ar ages on rocks from the same area.

A well-exposed volcanic field (150 km^2) located in the Blackburn Hills, about 10 km west of the Yukon River and 70

TABLE 1. INCOMPATIBLE ELEMENTS IN ANDESITES FROM THE KUSKOKWIM MOUNTAINS BELT*

	Von Frank (shoshonitic)	Nowitna (moderate to high-K)	Page Mountain (altered, probably high-K to shoshonitic)	Sleetemute (moderate-K)	Bristol Bay (moderate-K)	St. Matthew Island (low- to moderate-K)
	n = 5	n = 7	n = 7	n = 12	n = 6	n = 6
SiO_2	53.8 to 59.1	55.0 to 62.0	57.8 to 61.9	54.0 to 59.5	53.3 to 56.9	54.8 to 64.0
Nb	8 to 16	9 to 18	9 to 14	7.7 to 10.7	4 to 6	5 to 11
Zr	92 to 239	174 to 253	145 to 183	109 to 168	97 to 127	117 to 158
Y	17 to 25	22 to 33	14 to 25	17 to 26	21 to 32	23 to 26
Sr	911 to 1420	475 to 525	466 to 670	307 to 547	511 to 760	350 to 544
Rb	59 to 155	48 to 90	79 to 132	38 to 64	4 to 32	14 to 25
Ba	1792 to 2210	846 to 1350	1097 to 1870	349 to 910	376 to 786	318 to 470
La	49 to 57	30 to 44	25 to 37	12.8 to 28.8	12 to 21	1 to 16
Th	16.6 to 30.5	8.2 to 13.1	9.74 to 12.2	3.0 to 6.5	n.d.	1.0 to 2.0
Ta	0.902 to 1.18	0.79 to 1.13	0.664 to 0.85	0.43 to 1.06	n.d.	0.38 to 0.71
Hf	5.0 to 6.6	4.1 to 5.8	3.4 to 4.3	2.42 to 4.24	n.d.	2.5 to 4.1
$^{87}Sr/^{86}Sr$	0.7047 to 0.7051	0.70434 to 0.70508	0.7049 to 0.7059	0.70403 to 0.70601	0.70370 to 0.70414	n.d.

*Note: Von Frank, Nowitna, and Page Mountain are in the northern Kuskokwim Mountains, Sleetemute is in the central Kuskokwim Mountains, and Bristol Bay is at the southern end of the Kuskokwim Mountains. Incompatible elements increase from north to south, left to right. SiO_2 is in weight percent, all other elements are in parts per million.

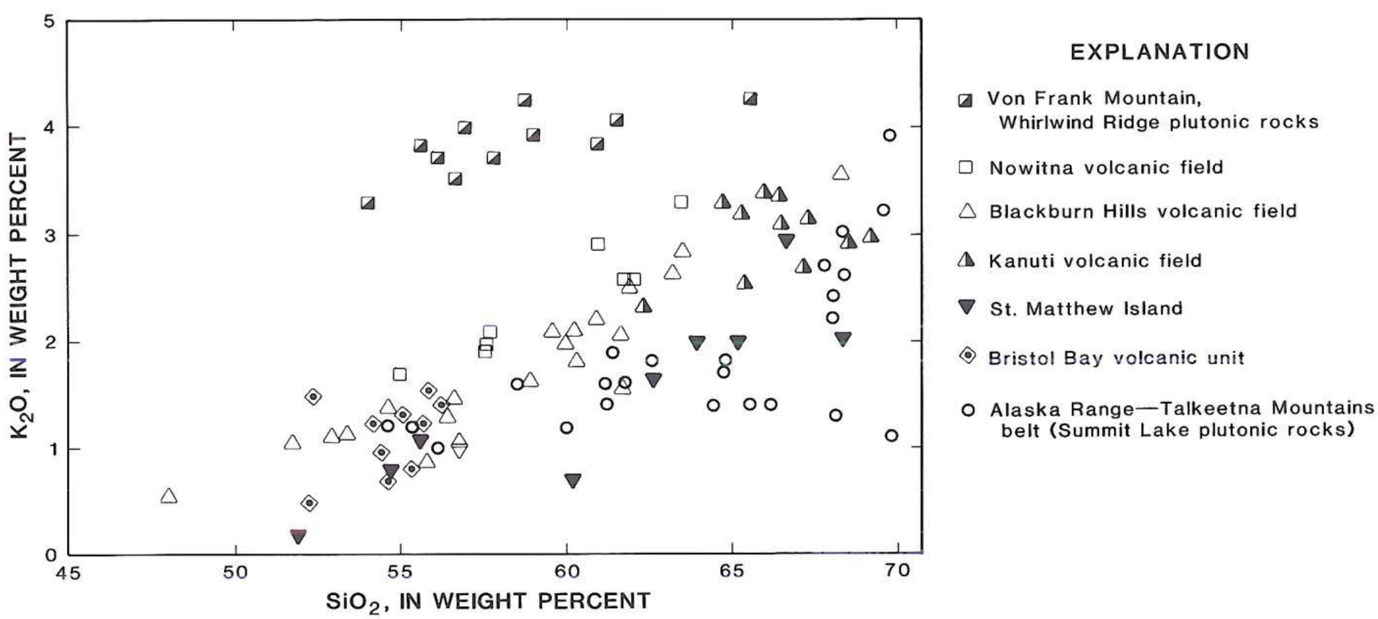


Figure 5. K_2O versus SiO_2 for Late Cretaceous and early Tertiary volcanic and plutonic suites. Alaska Range–Talkeetna Mountains belt (Summit Lake plutonic rocks: Reed and Lanphere, 1974a); St. Matthew Island; southern Kuskokwim Mountains (Bristol Bay volcanic unit); northern Kuskokwim Mountains (Nowitna volcanic field and Von Frank Mountain pluton–shoshonitic suite); Yukon-Kanuti belt (Blackburn Hills and Kanuti volcanic fields).

km south of the Kaltag fault (number 1 on Fig. 1), consists of a thick section of andesite flows exposed in a northeast-trending syncline that is bounded by the Thompson Creek fault on the west flank and by an unnamed fault on the northwest flank. The flows are interlayered with rhyolite domes and basalt flows near the top of the section. The core of the syncline consists of a thick section of highly altered green tuff intruded by a granodiorite pluton. The base of the volcanic pile is dated at 65 Ma; the rhyolite domes and granodiorite pluton at 56 Ma (Patton and Moll, 1985; Moll-Stalcup, 1987). The green altered tuff is interpreted as intracaldera tuff, and the granodiorite pluton is interpreted as an eroded resurgent dome (Moll-Stalcup, 1987).

A thick sequence of east-dipping andesite flows crop out in low hills about 20 km south of the Blackburn Hills on the opposite side of the Thompson Creek fault. Available data suggest that these flows are part of the west flank of the Blackburn Hills volcanic field, which in turn suggests that 20 km of left-lateral movement has taken place along the Thompson Creek fault since early Tertiary time.

Petrogenesis. The Yukon-Kanuti belt is generally similar to the Kuskokwim Mountain belt in that it consists of moderate- to high-K calc-alkalic suites of mafic to felsic compositions. Basalt, however, is more abundant in the Yukon-Kanuti belt, although still much less common than andesite. A further distinction between the two belts is that most rocks in the Yukon-Kanuti belt having 63 to 68 percent SiO_2 are volcanic rather than intrusive.

The Blackburn Hills volcanic field consists of a thick pile (1 km) of chiefly andesite flows at the base, and interlayered rhyolite, basalt, and andesite at the top. The lower andesite section is divided into two groups on the basis of REE patterns: One group consists of one- and two-pyroxene andesites and basalts that have REE patterns similar to the andesites in the northern Kuskokwim Mountains (Fig. 4D, G). The second group consists of hornblende and pyroxene andesites that have higher LREE and lower HREE than the first group (Fig. 4H). Rocks in the second group also have lower FeO* and TiO_2, and higher MgO at a given SiO_2, and higher initial $^{87}Sr/^{86}Sr$ than the first group, and they occur only in the northwest part of the volcanic field. The rhyolites at the top of the section have a wide variety of mineral assemblages; some are typical of calc-alkalic suites, and some of mildly alkalic rocks. Common mineral assemblages include anorthoclase+hedenbergite, oligoclase+biotite, and oligoclase+orthopyroxene.

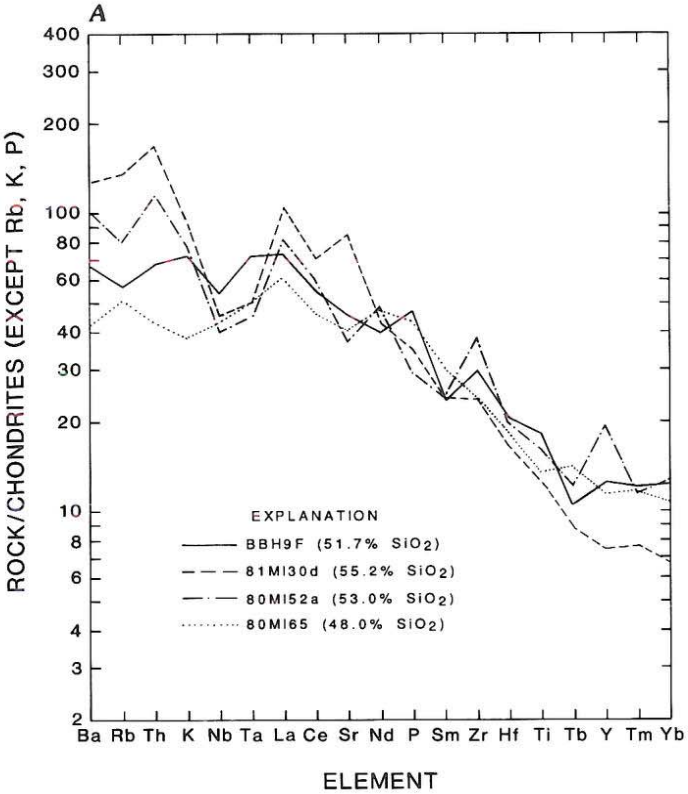
The occurrence of both calc-alkalic and mildly alkalic suites at the top of the Blackburn Hills section suggests that there was a chemical and mineralogical transition at about 56 Ma. Rocks that are older than 56 Ma are compositionally similar to those in the Kuskokwim Mountains belt in that the andesites are enriched in K, Rb, B, Th, U, and Sr and depleted in Nb and Ta, relative to the LREE (Fig. 6A). These andesites contain minerals typical of calc-alkalic rocks such as plagioclase, orthopyroxene, clinopyroxene, and hornblende. Rocks between 56 and 46 Ma constitute a mixed assemblage of calc-alkalic and mildly alkalic rocks, which occur at the top of the Blackburn Hills section and in the nearby Yukon River area. Some of the post–56 Ma rocks show the characteristic enrichments and depletions and have the typical calc-alkalic mineralogy (rhyolites: plag+biot; andesites: plag+opx+cpx) of the earlier suite. The post–56 Ma assemblage differs, however, in that: (1) there is a higher proportion of basalt and these basalts have smaller Nb-Ta depletions and lower alkali/LREE ratios than typical arc rocks (Fig. 6A; Thompson and others, 1982); and (2) some of the rhyolites have mildly alkalic mineral assemblages, such as anorthoclase+hedenbergite (Moll-Stalcup, 1987). This chemical and mineralogical transition is not strongly reflected in the major-element data, which indicate a calc-alkaline affinity for all the rocks.

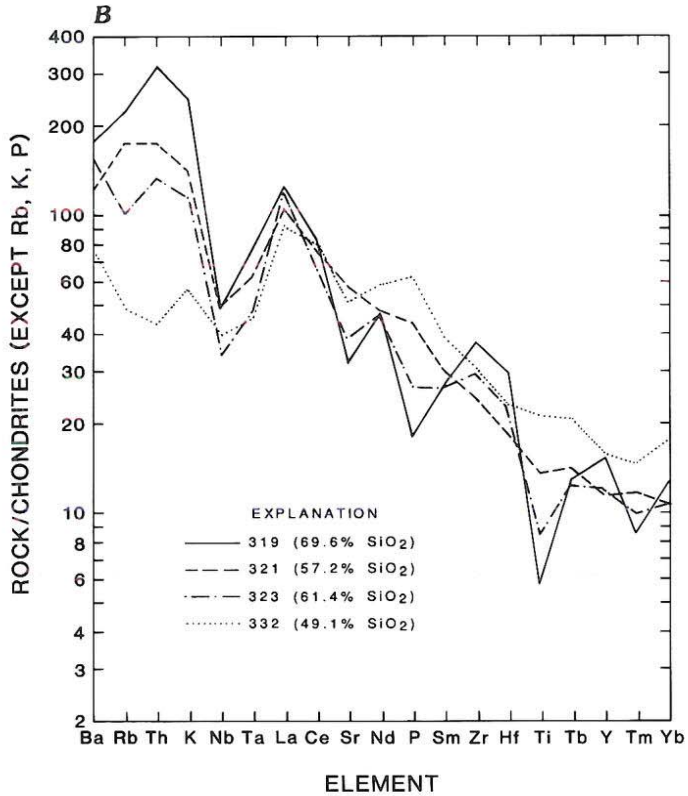
The shift in mineralogy and chemistry upsection is found only in the Blackburn Hills field. The rocks in the Yukon River area (53 to 47 Ma) postdate the transition, whereas the rocks in the Kanuti field (59 to 56 Ma) predate the transition. The volcanic rocks in the Yukon River area include a mixed assemblage of typical calc-alkalic andesites and dacites (andesite: plag+opx+cpx; dacite: plag+horn+biot) and mildly alkalic latites and basalts (latites: anorthoclase+plag+biot; basalt: ol+plag+cpx and groundmass ol+biot). Rocks containing calc-alkalic mineral assemblages have moderate Nb-Ta depletions (La/Nb greater than 2); rocks with mildly alkalic mineral assemblages have smaller Nb-Ta depletions. No correlation between age and rock types has been found in the Yukon River area, and it appears that both calc-alkalic "arc-type" and mildly alkalic "post–arc-type" rocks erupted between 53 and 47 Ma.

The Kanuti volcanic field is dated at 59 to 56 Ma and predates the transition noted at the southern end of the belt. All the analyzed rocks from the Kanuti field have a high alkali and LREE content and deep troughs at Nb and Ta on chondrite-normalized multi-element plots (Fig. 6C), similar to the older suite of rocks in the Blackburn Hills. The volcanic rocks in the Kanuti field range from high-silica andesite to rhyodacite. Most contain hornblende and have REE patterns similar to hornblende-bearing andesites in the Blackburn Hills (Fig. 5A).

Samples of andesite, basalt, and dacite that give K/Ar ages of 59.8 to 50.2 Ma have been dredged from the edge of the Bering Sea shelf (Fig. 1; Davis and others, 1987, 1989). These rocks are altered but appear to have typical calc-alkalic compositions and may be correlative with the Yukon-Kanuti belt. Whether they are part of the Yukon-Kanuti or some other belt, however, is not known. They may be rocks that were accreted to the continental margin after eruption.

Volcanic rocks that have K-Ar ages from 64 to 62 Ma also occur on St. Lawrence Island in the Bering Sea. Patton and Csejtey (1980) describe them as basalt, soda rhyolite, trachyandesite, and andesite. Chemical analyses (W. W. Patton, Jr., unpublished data, 1971) suggest the rocks are mildly alkalic and possibly a bimodal basalt-rhyolite assemblage (SiO_2 48 percent and 68 to 71 percent). The K-Ar ages and mildly alkaline compositions suggest that the rocks are probably not part of any of the Late Cretaceous and early Tertiary belts, but they could be part of the Yukon-Kanuti belt if the transition from subduction-related





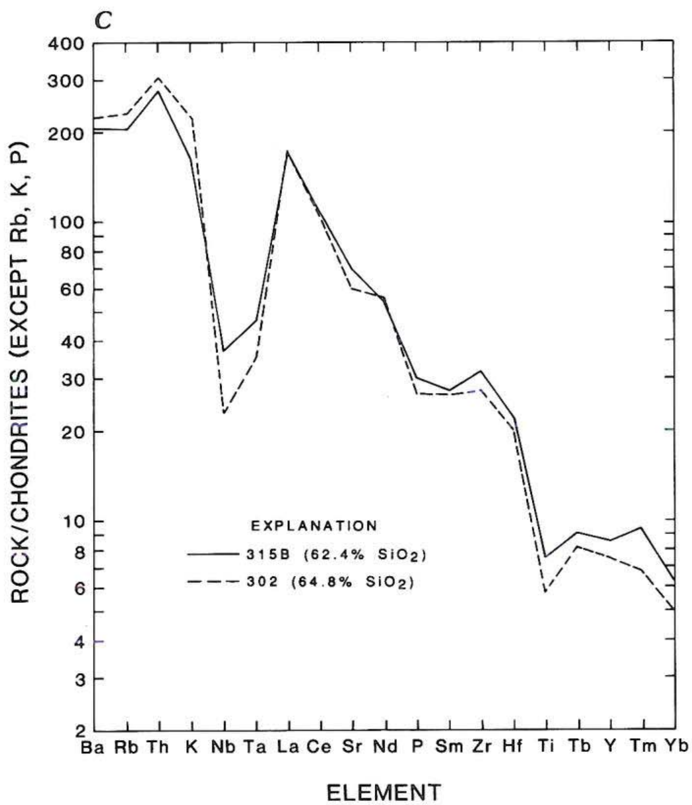


Figure 6. Chondrite-normalized spidergrams. A, samples from the Blackburn Hills in the Yukon–Kanuti belt. Samples 80ML52a and 81ML30d are from the older andesite section; samples 80ML9f and 80ML65 are basalts that overlie rhyolite domes or flows and are younger than 56 Ma. The younger rocks are more mafic, have lower alkalis relative to La and smaller Nb-Ta depletions. B, samples from Yukon River Eocene volcanic rocks. All data from E. J. Moll-Stalcup and W. W. Patton, Jr. (unpublished data, 1981). All the rocks except 81Pa332, a basalt dated at 53 Ma, have large Nb-Ta anomalies. The more siliceous rocks have negative spikes at Sr, P, and Ti due to fractionation. C, samples from the Kanuti volcanic field. All data from E. J. Moll-Stalcup and W. W. Patton, Jr. (unpublished data, 1980–1981).

calc-alkalic rocks to mildly alkalic post-subduction magmatism occurred earlier in that part of the Bering Sea.

Late Cretaceous and early Tertiary tectonic implications

The Alaska Range–Talkeetna Mountains, the Kuskokwim Mountains, and the Yukon-Kanuti belts constitute a Late Cretaceous and early Tertiary magmatic province that extends over a vast region of Alaska, from the Alaska Range north to the Arctic Circle and west to the Bering Sea shelf. The volcanic and plutonic rocks in this province overlap a number of tectonostratigraphic terranes that lie between the Alaska Range, Bristol Bay, and the Yukon-Koyukuk province, which suggests that these terranes were assembled by late Mesozoic time (Moll and Patton, 1982). Paleomagnetic studies of Late Cretaceous and early Tertiary volcanic rocks at Bristol Bay (Globerman, 1985), Lake Clark (Thrupp and Coe, 1986), the northern Kuskokwim Mountains (Nowitna field, Coe and others, 1985; Blackburn Hills field, Thrupp and Coe, 1986), the Talkeetna Mountains (Hillhouse and others, 1985), and the east-central Alaska Range (Cantwell Formation, Hillhouse and Gromme, 1982) indicate about 30 to 55° of counterclockwise rotation, but no major latitudinal displacement relative to North America since eruption (Hillhouse and Coe, this volume; Thrupp and Coe, 1986).

Igneous rocks erupted between 75 and 56 Ma from all three belts have chemical compositions typical of subduction-related magmatism. Dominant compositions are intermediate and felsic, and rocks from all three belts have high K, Ba, Sr, Rb, and Th, and low Nb, Ta, and Ti relative to LREE—the most diagnostic characteristics of arc magmatism. Most workers (e.g., Hudson, 1979; Reed and Lanphere, 1973) agree that the Alaska Range–Talkeetna Mountains belt is a continental volcanic arc related to subduction of the Kula plate under southern Alaska during the Paleocene. The tectonic environment of the Kuskokwim Mountains and Yukon-Kanuti belts has not been so well documented. Wallace and Engebretson (1984) outline three possible relations between the Alaska Range–Talkeetna Mountains and Kuskokwim Mountains belts: (1) the Kuskokwim Mountains belt formed in an extensional environment (or intracontinental back-arc setting) behind the Alaska Range–Talkeetna Mountains belt (Bundtzen and Gilbert, 1983; Gemuts and others, 1983); (2) the Alaska Range–Talkeetna Mountains and Kuskokwim Mountains belts constitute an unusually wide arc analogous to Oligocene volcanism in the western U.S. (Gill, 1981, p. 39, and references therein); or (3) the Alaska Range–Talkeetna Mountains and the Kuskokwim Mountains belts were two separate arcs juxtaposed by subsequent tectonic activity. Of the three possibilities, the third is the least likely because no major Tertiary suture has been mapped between the two belts, and geologic and paleomagnetic data suggest that the two belts were essentially in place during formation—not accreted at some later time. Both belts may have been brought into their current position by strike-slip faults, but Tertiary offsets along faults in western Alaska are thought to be relatively small, probably less than 150 km (Grantz, 1966). Finally, the abundance of high-K calc-alkalic and shoshonitic rocks in the Kuskokwim Mountains suggest that it was not a piece of the Alaska Range–Talkeetna Mountains belt that was originally along strike and was later strike-slip faulted to its present position.

The chemical composition of the plutonic and volcanic rocks in the Kuskokwim Mountains and Yukon-Kanuti belts strongly supports their formation in an arc rather than back-arc environment. Other workers (T. K. Bundtzen and S. E. Swanson, written communication, 1986) have argued that the Kuskokwim Mountains magmatism is the result of regional extension because many of the rocks in the northern Kuskokwim Mountains have high contents of total alkalis, and therefore plot in the alkalic field on total-alkalis-versus-silica diagrams, and the volcanic fields and intrusive rocks are associated with numerous normal/strike-slip faults. I distinguish between arc-related alkalic rocks (shoshonites) that are characterized by K_2O/Na_2O greater than, or equal to 1, low TiO_2 and high-field-strength-element contents, and high alkalis and Al_2O_3 contents (Morrison, 1980; Bloomer and others, 1989) and other types of alkalic rocks that have higher contents of Ti, Nb, Ta, and Zr. Although earlier workers believed most of the rocks were basalts and rhyolites and therefore constituted a bimodal assemblage, many of the chemical analyses published on earlier maps (Bundtzen and Laird, 1982, 1983a, b, c) have SiO_2 more than 53 percent, when the analyses are recalculated 100 percent anhydrous. Of 49 analyses having LOI less than 10 percent, 4 have less than 53 percent SiO_2, 36 have 53 to 63 percent SiO_2, 4 have 63 to 70 percent SiO_2 (all plutonic), and 4 have more than 70 percent SiO_2. Rocks having more than 53 percent SiO_2 are andesites even when they are olivine-bearing, because olivine is stable at higher silica contents in high-K suites than in low or moderate-K suites (Kushiro, 1975). Furthermore, the silica gap in the published data occurs in the dacite range (63 to 70 percent SiO_2), which is not uncommon in modern arc volcanoes (Grove and Donnelly, 1986) and is distinct from the Miocene bimodal basalt-rhyolite suite associated with extension in the western United States (Christiansen and Lipman, 1972). Bundtzen and Swanson's argument for extension based on the abundance of faults is discussed further below.

The chemical data strongly support the interpretation that the Alaska Range–Talkeetna Mountains, Kuskokwim Mountains, and Yukon-Kanuti belts constituted an anomalously wide magmatic arc in the Late Cretaceous and early Tertiary, analogous to the western United States in the Oligocene. In their present configuration the three belts span a width of 550 km, extending approximately 990 km measured orthogonal to the Aleutian trench near the Alaska Peninsula. In the conterminous states, Oligocene volcanism as far east as the Rocky Mountains has been attributed to convergence along the western continental margin (Lipman and others, 1972; Snyder and others, 1976). The compositions of andesites in the northern Kuskokwim Mountains are remarkably similar to those in the Oligocene San Juan volcanic field in Colorado (Table 2; Lipman and others, 1978), which also was located at least 900 km from the Oligocene continental margin.

TABLE 2. TRACE ELEMENT ABUNDANCES (ppm) AND RATIOS IN REPRESENTATIVE ANDESITE SAMPLES FROM THE SAN JUAN VOLCANIC FIELD (SUMMER COON), COLORADO, AND FROM THE NORTHERN KUSKOKWIM MOUNTAINS BELT (NOWITNA) AND THE YUKON–KANUTI BELT (BLACKBURN HILLS), ALASKA

	Summer Coon*	Nowitna†	Blackburn Hills†
(wt %)			
SiO_2	56	57	56.5
Rb (ppm)	65	52	35
Ba (ppm)	1,160	870	891
Sr (ppm)	930	505	493
K/Rb	344	298	299
La (ppm)	30	32	30
Ce (ppm)	79	66	52
Yb (ppm)	1.5	2.4	2.2
La/Yb	20	13.3	13.6
Th (ppm)	3.6	8.3	6.1
U (ppm)	1.1	3.1	2.2
Th/U	3.2	2.7	2.8

*Zielinski and Lipman (1976)
†Moll-Stalcup (1987)

Interpreting trends in K_2O within and among the three belts is complex because the three belts cut across numerous terranes of different age and lithology. K_2O contents are higher in the Kuskokwim Mountains and Yukon-Kanuti belt (Fig. 5) than in the Alaska Range–Talkeetna Mountains belt, as expected in an arc environment if the trench was located along the southern margin of Alaska. However, rocks in the northern Kuskokwim Mountains have higher K_2O-contents than those in either the southern Kuskokwim Mountains belt or the Yukon-Kanuti belt. As discussed earlier, high K_2O (and all incompatible element) contents in the northern Kuskokwim Mountains belt appears to be related to interaction of the magmas with old, possibly thicker, continental crust or lithospheric mantle. Even moderate-K rocks in the northern Kuskokwim Mountains have higher K and incompatible-element contents than rocks from any of the other areas or belts, suggesting that the magmas in the northern Kuskokwim Mountains have interacted with old continental crust or mantle, which has resulted in their enriched composition. However, K contents in Late Cretaceous and early Tertiary rocks from the northern Kuskokwim Mountains vary from moderate-K to high-K to shoshonitic, so not all of the K variation can be attributed to the age and thickness of the underlying lithosphere. Some must be the result of some other factor, such as changing depth to the subducting slab.

The age data suggest that between 75 and 65 Ma the magmatic arc was narrower, consisting chiefly of the Alaska Range–Talkeetna Mountains and Kuskokwim Mountains belts, and that the K gradient across the arc was steeper. During this period the K-content in the magmas increased across the arc, from moderate-K in the southern Alaska Range–Talkeetna Mountains belt, to high-K and shoshonitic in the northern Kuskokwim Mountains. Much of this steep gradient in K, across the Alaska Range–Talkeetna Mountains to the Kuskokwim Mountains belt, was probably tectonically controlled by increasing depth to the slab, but some K-enrichment in the northern Kuskokwim Mountains was due to lithospheric interaction.

During the period from 65 to 56 Ma, the arc broadened to include the Yukon-Kanuti belt, and the K gradient across the arc was more gradual, probably due to a decrease in dip of the subducting slab. During this time period, K_2O at a given silica content was lower in the Yukon-Kanuti belt than in the northern Kuskokwim Mountains, despite the fact that the Kuskokwim Mountains rocks were closer to the trench. This reversal in K trend across the arc is interpreted to be a result of interaction between old, enriched lithosphere and arc magmas in the northern Kuskokwim Mountains region. Variation in crustal thickness could be a factor in the K_2O gradient, but is not indicated by the gravity data. Gravity studies suggest that the present-day crust under both the Yukon-Kanuti belt, in the study area, and the northern Kuskokwim Mountains is between 30 and 35 km thick (Barnes, 1977). Although crustal thicknesses may have changed since the early Tertiary, they probably have not because the Tertiary has been characterized by mild deformation (open folds and strike-slip faulting) and low sedimentation rates.

The K_2O content of the arc magmas in the southern Kuskokwim Mountains belt (Bristol Bay volcanic rocks) is about the same as in the Yukon-Kanuti belt, both of which are underlain by late Paleozoic and Mesozoic oceanic crust and island-arc rocks of the Yukon-Koyukuk province and Togiak terrane (Fig. 5). These late Paleozoic and Mesozoic mafic and intermediate basement rocks would be expected to have much lower incompatible-element contents, lower $^{87}Sr/^{86}Sr$, and higher $^{143}Nd/^{144}Nd$ than the old sialic continental crustal rocks of the Ruby and Nixon Fork terranes, which underlie the northern Kuskokwim Mountains. The strong contrast between basement lithologies is evident in trace-element and isotope composition of rhyolites from each area. Rhyolites from the Blackburn Hills, in the Yukon-Kanuti belt, have lower LREE, Rb, Th, U, Sn, F, and initial $^{87}Sr/^{86}Sr$, and higher $^{143}Nd/^{144}Nd$ than rhyolites from the northern Kuskokwim Mountains (Moll and Patton, 1983; Moll and Arth, 1985; Moll-Stalcup and Arth, 1989). Andesites from the Nowitna volcanic field show evidence of interaction with enriched continental crust, whereas those from the Blackburn Hills do not (Moll and Arth, 1985; Moll-Stalcup and Arth, 1989). I attribute the very high K_2O and incompatible-element contents in the northern Kuskokwim Mountains magmas to interaction with old sialic crust in that area. Such old crust might also affect the K_2O gradient along the arc, from north to south, as well as cause the reversal in K_2O gradient across the arc from the northern Kuskokwim Mountains to the Yukon-Kanuti belt. Interaction with the crust seems especially common in subduction-related suites because these magmas rise slowly to the surface and have ample time to differentiate and assimilate country rock.

Bundtzen and Swanson (1984) note that many of the Late Cretaceous and early Tertiary volcanic and intrusive bodies are associated with normal or strike-slip faults. Little is known about the age and type of motion for most of these faults, but most appear to have significant right-lateral movement (Grantz, 1966). Some of the volcanic fields are cut by normal strike-slip faults, but it is uncertain whether the faults entirely postdate the volcanism, and thus control only the exposure of the volcanic fields, or if some of the volcanism was contemporaneous with, or postdates the faulting. Rhyolite domes dated at 58 Ma occur at Old Woman Mountain in the Kaltag fault zone just west of the Yukon River (W. W. Patton, Jr., and E. J. Moll, unpublished data, 1983), and similar domes dated at 61 Ma occur in the Nixon Fork–Iditarod fault zone near McGrath (Bundtzen and Laird, 1983c). Some of these rhyolite domes thus appear to have intruded into preexisting fault zones. In addition, some felsic dikes or sills of Late Cretaceous and early Tertiary age strike parallel to major faults (Patton and others, 1980; Bundtzen and Laird, 1983b), which suggests some of the faulting had occurred by the time the dikes and sills were emplaced. Most of the Late Cretaceous and early Tertiary volcanic piles are gently folded, with maximum dips of 20 to 45 degrees, but most of the Middle Tertiary volcanic piles are flat lying and undeformed (Harris, 1985; W. W. Patton, Jr., personal communication, 1986). These data demonstrate that at least some of the deformation postdates the Late Cretaceous and early Tertiary magmatism, and also suggests that some may have been contemporaneous with or predated it. I believe that these equivocal relations do not support the interpretation that the magmatism is the result of continental rifting. The chemical composition of rocks in both the Yukon-Kanuti and Kuskokwim Mountains belts was dominantly controlled by subduction, not continental rifting. Although the timing of movement along the faults is not well constrained, I find the idea that most of the movement along the faults took place in the Eocene and was related to the clockwise rotation or oroclinal bending of western Alaska (Globerman and Coe, 1984) very appealing. The implications of this idea are discussed further below.

In contrast to the 75- to 56-Ma rocks, many of the rocks in western Alaska that are 56 m.y. old or younger have chemistry and mineralogy that are not typical of subduction-related magmas. These rocks include the McKinley sequence granites and the quartz monzonite of Tired Pup in the western and northern Alaska Range, the rhyolites and basalts at the top of the Blackburn Hills, and the volcanic rocks in the Yukon River area in the Yukon-Kanuti belt. I believe subduction-related magmatism in western Alaska ceased at about 56 Ma, and the period from 56 to 50 Ma represents a transition from subduction-related magmatism to post-subduction, possibly intraplate, magmatism, during which rocks typical of both environments erupted. This transition period is marked by: (1) a marked decrease in the volume of magma erupted over the entire province; (2) an increase in the proportion of basalt and the eruption of mildly alkalic basalt, latite, and alkali rhyolite in the Yukon-Kanuti belt; and (3) the emplacement of peraluminous silicic granites of the McKinley sequence in the northern and western Alaska Range. Subduction-related volcanism younger than 56 Ma occurred in the Talkeetna Mountains at the eastern end of the Alaska Range–Talkeetna Mountains belt, but insufficient petrologic data are available on these rocks to determine whether a similar chemical or mineralogical transition marked the end of subduction-related magmatism there.

In summary, the age and composition data suggest that the Alaska Range–Talkeetna Mountains, Kuskokwim Mountains, and Yukon-Kanuti belts constituted an anomalously wide magmatic arc related to north-directed subduction at a trench along the Paleocene continental margin of Alaska (Fig. 1) between 75 and 56 Ma. The data also suggest that only the southeastern two-thirds of the province was active between 75 and 66 Ma, broadening to the entire province between 66 and 56 Ma. A sharp decrease in magma volume and a mineralogical and compositional change at 56 Ma mark the end of the subduction event in most of the province except the easternmost end of the province in the Talkeetna Mountains.

Plate-motion models (Engebretson and others, 1982) show rapid north-northeast–directed subduction of the Kula plate under southern Alaska between 74 and 56 Ma. In early Eocene time, the trench jumped out to its present position, and the Aleutian arc began to form (Rea and Duncan, 1986; Scholl and others, 1986). The convergence angle between the present position of the three belts and the Paleocene plate-motion vectors is near the minimum (25°) required for arc magmatism (Gill, 1981, p. 27; Wallace and Engebretson, 1984). Paleomagnetic data on the volcanic rocks indicate that western Alaska has rotated counter-clockwise 30 to 55° but has not been latitudinally displaced since the Paleocene (Globerman and Coe, 1984; Hillhouse and Coe, this volume). These data suggest that the magmatic belts may have had a convergence angle of 55 to 80° prior to rotation in the Eocene. Paleomagnetic data from the Ghost Rocks Formation on Kodiak Island in southern Alaska indicate it has moved 2,000 km to the north since the Paleocene (Plumley and others, 1982). These data suggest that a Tertiary suture associated with the accretion of southernmost Alaska should be located somewhere between southern Kodiak Island and the Alaska Range batholith (Thrupp and Coe, 1986). This hypothetical suture may represent a strike-slip fault (Moore and others, 1983) or the subduction zone associated with the wide Late Cretaceous and early Tertiary magmatic province.

The location of the magmatic belts relative to the trench is further obscured by numerous right-lateral strike-slip faults, which have apparently cut the wide magmatic arc since the Paleocene. The amount of offset since the Paleocene is not known. Most data suggest that the amount of offset along the strike-slip faults in western Alaska is considerably less than the amount of offset along the faults in eastern Alaska (Grantz, 1966). The

Yukon-Kanuti belt appears to be offset along the Kaltag fault, which Patton and Hoare (1968) suggest has had 60 to 130 km of right-lateral offset since the Late Cretaceous. If movement on faults is reconstructed and the trench is located along the northern part of Kodiak Island, the entire magmatic arc was within 750 km of the trench when it was active.

MIDDLE TERTIARY MAGMATISM

The period from 55 to 43 Ma was characterized by a hiatus in magmatic activity in most of mainland Alaska except along the hinge line of the Alaska orocline (Talkeetna Mountains, Arkose Ridge, Prince William Sound, and Yakutat terrane), the Sanak-Baranof belt (Hudson, this volume), and the Yukon River area. Small amounts of volcanic activity occurred in the Aleutian arc and Alaska Peninsula from 50 to 43 Ma (Scholl and others, 1986; Wilson, 1985; Vallier and others, this volume; Kay and Kay, this volume; Miller and Richter, this volume). At about 40 Ma (±3), a brief magmatic pulse occurred in western interior Alaska, and a major pulse of magmatic activity, which lasted 10 m.y., began in the Aleutian arc. The arc volcanism occurred in a narrow belt extending from the Aleutian Islands probably as far northeast as Sugar Loaf Mountain on the north side of the Denali fault in the central Alaska Range (Plate 5). Magmatism on the Aleutian Islands, on the west side of the Alaska Peninsula (the so-called Meshik arc of Wilson, 1985), on the north and west flank of the Alaska–Aleutian Range batholith (Merill Pass of Reed and Lanphere, 1973), at Mount Foraker and McGonagall (Reed and Lanphere, 1974b), at Mount Galen (Decker and Gilbert, 1978), and possibly as far east as Sugarloaf Mountain (Albanese, 1980; Albanese and Turner, 1980) was probably part of the mid-Tertiary Alaska-Aleutian arc.

The Talkeetna Mountains and Yukon River areas were discussed in the previous section and are interpreted as the last remnants of a widespread Late Cretaceous and early Tertiary subduction event in western and southern Alaska. Eocene dikes in Prince William Sound are listed in Table 1 on Plate 5 and are described in more detail by Hudson (this volume), who considers them part of the Sanak-Baranof belt of anatectic granites. The Eocene volcanic rocks in south-central and western interior Alaska are described below.

South-central Alaska

Although most of mainland Alaska experienced relative quiescence between 55 and 43 Ma, volcanic and plutonic rocks of this age occur in the hinge of the Alaska orocline in an area between the Border Ranges and Denali fault or in the southern accretionary wedge south of the Border Ranges fault. Rocks in the hinge area include the Arkose Ridge Formation, the Talkeetna Mountains volcanic rocks, and many unnamed plutons in the northern Talkeetna Mountains.

Basalt dikes, sills, and altered tholeiitic flows (55 to 43 Ma) occur in the Arkose Ridge Formation of southern Alaska, just south of the Talkeetna Mountains volcanic rocks (Silberman and Grantz, 1984). A. Grantz (personal communication, 1986) considers these rocks to be late Paleocene in age on the basis of plant fossils in interbedded sandstones. The rocks have smaller Nb-Ta depletions on multi-element diagrams than do contemporaneous arc rocks in the Talkeetna Mountains (Fig. 7), but their trace-element ratios do not unambiguously resolve whether they are arc tholeiites related to subduction or intraplate volcanic rocks possibly related to the Castle Mountain fault. Therefore, both their tectonic environment and their precise age are uncertain.

Early to middle Eocene basaltic flows, hyaloclastites, and flow breccias, along with interbedded clastic marine sedimentary rocks, occur in the Yakutat terrane south of the Border Ranges fault (Davis and Plafker, 1986). The basalts consist of LILE-depleted and LILE-enriched tholeiites, which Davis and Plafker (1986) interpret as normal mid-ocean ridge and oceanic island basalt. They suggest that these basalts are correlative with contemporaneous geochemically similar basalts, which occur in a linear belt extending from southern Vancouver Island to the southern Oregon Coast Range. They further suggest that the basalts originated as seamounts near the Kula-Farallon spreading center in the early to middle Eocene, and were accreted to the

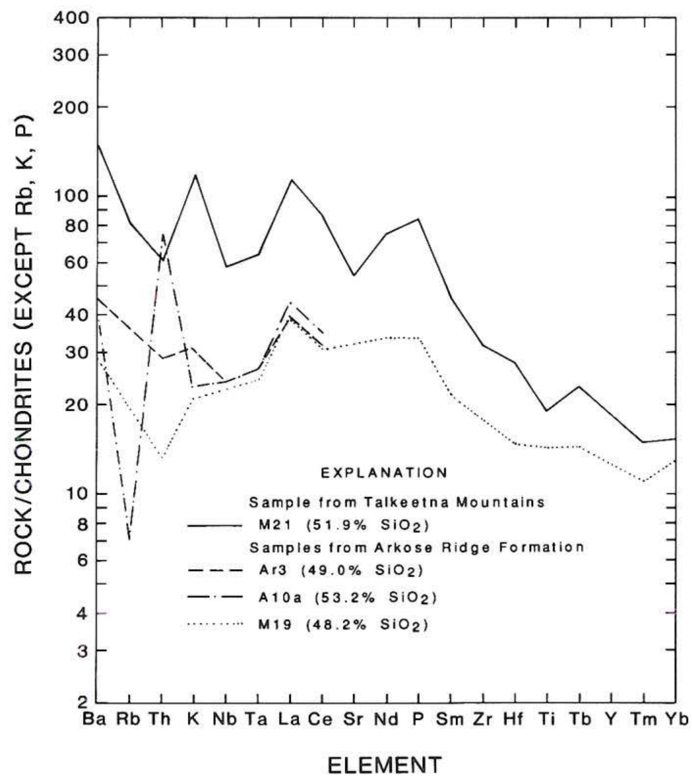


Figure 7. Chondrite-normalized spidergrams for the Arkose Ridge Formation and Talkeetna Mountains volcanic rocks. Data from A. Grantz and M. L. Silberman (unpublished data, 1981). The variation in the shape of the pattern for the Arkose Ridge samples for Ba, Rb, Th, and K suggests that these rocks are altered.

southern continental margin of Alaska at about 48 Ma during subduction of the Kula-Farallon ridge and Kula plate.

Western Interior Alaska

Volcanic rocks (37 to 43 Ma) occur on St. Lawrence Island, in the Melozitna area, in the Yukon River area, and in the Sleetmute area (Fig. 8). Limited data suggest that these constitute a bimodal assemblage of felsic volcanic rocks and associated basalt that have calc-alkalic to mildly alkalic affinities.

Patton and Csejtey (1980) describe volcanic rocks on St. Lawrence Island (39.3 Ma) as rhyolite and dacite tuff, tuff breccia, and flows. The unit is not well exposed but is thought to be flat-lying or gently dipping (Patton and Csejtey, 1980).

Three volcanic fields (40 ± 3 Ma) occur between the Melozitna and Koyukuk Rivers on the north side of the Kaltag fault at Indian Mountain, Takhakhdona Hills, and Dulbi River. All three consist chiefly of rhyolite tuff, flows, and breccia (Patton and others, 1978). Dark vesicular basalt flows (Patton and others, 1978) and andesite and dacite (Patton and Moll-Stalcup, unpublished data, 1989) also occur in the Takhakhdona Hills. Rhyolite obsidian (39.9 to 41.6 Ma) occurs at Indian Mountain (Miller and Lanphere, 1981) and is a possible source of the obsidian artifacts found in northwestern Alaska (Patton and Miller, 1970).

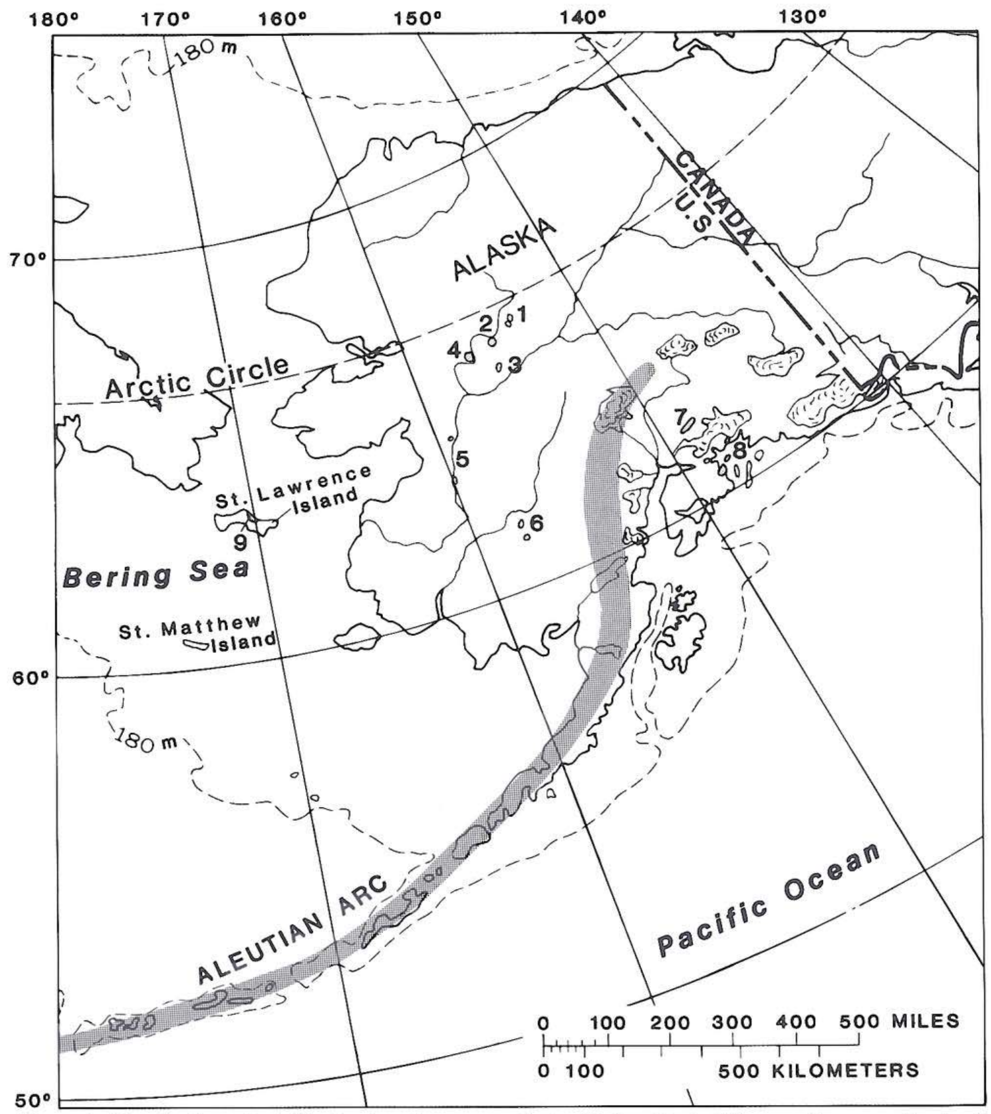


Figure 8. Distribution of middle Tertiary igneous rocks in Alaska. Dashed line marks water depth of 180 m. Middle Tertiary Alaska–Aleutian Range arc shown in shaded pattern. Middle Tertiary igneous localities shown in red. Locations are: 1, Indian Mountain; 2, Dulbi River; 3, Takhakhdona Hills; 4, Kateel River; 5, Yukon River; 6, Sleetmute area; 7, Matanuska Valley and Arkose Ridge; 8, Prince William Sound; and 9, St. Lawrence Island.

Harris (1985) reports K-Ar ages of 40 ± 3 Ma at two localities on the Yukon River, one north of Morgan Island in the southernmost Nulato Quadrangle (42.7 Ma) and one near the village of Grayling in the northernmost Holy Cross Quadrangle (42.4 Ma). He also reports that the Oligocene volcanic rocks are flat-lying and undeformed. No lithologic data are given, but at least some are basalt because the K-Ar dates were run on basalt whole-rock samples. Additional volcanic rocks of this age may occur farther south in the Holy Cross Quadrangle, where widespread undated volcanic rocks are exposed.

Little-known volcanic rocks in this age range occur in the Sleetmute area. Olivine basalt (38.2 Ma) is reported from the Chuilnuk River area, and a rhyolite sequence (43.8 Ma) is reported from Tang Mountain (Decker and others, 1986). The rhyolites at Tang Mountain are apparently interbedded(?) with trachyandesite near the base of the rhyolite section. Decker and others (1986) describe a black glassy rhyolite unit, probably a basal vitrophyre, overlain by a gray rhyolite unit.

Petrogenesis. Few petrologic data are available for the middle Tertiary volcanic rocks in western interior Alaska. Major-element data from St. Lawrence Island, Indian Mountain, the Takhakhdona Hills, and Tang Mountain suggest that the rocks are dominantly felsic (66 to 77 percent SiO_2), along with minor mildly alkalic basalt and andesite. Basalt occurs in the Takhakhdona Hills and Yukon River area; andesite occurs at Tang Mountain. No chemical or mineralogical data are available for the basalt on the Yukon River. Rocks in the Takhakhdona Hills range from basalt through rhyolite, and appear to have arc-like patterns on multi-element spidergrams (Fig. 9). Chemical analyses of the andesite at Tang Mountain (Decker and others, 1986) show that the rock has high TiO_2 (1.97 percent), K_2O (3.00 percent), Nb (49 ppm), Ta (3.85 ppm), and La (51 ppm) and low Ba (445 ppm). The composition of this rock, along with its trace-element ratios (Ba/Ta = 116, La/Nb = 1.03), suggests it is not a subduction-related orogenic andesite but a trachyandesite of some other affinity. Normalized multi-element data on trachyandesites from Tang Mountain show very high LREE and virtually no Nb-Ta depletion (Fig. 9). The initial $^{87}Sr/^{86}Sr$ on the same rock is 0.7033, much lower than initial $^{87}Sr/^{86}Sr$ on the Late Cretaceous and early Tertiary rocks from the same area.

Mineralogical data are available only for rocks from a few localities and are summarized in Table 1 on Plate 5. Most of the felsic rocks have minerals typical of calc-alkalic rocks, but some are more alkalic. Dacite having anorthoclase, plagioclase, biotite, and oxides, and rhyolite having anorthoclase, plagioclase, and biotite have been reported from the Takhakhdona Hills, and trachyandesite having sanidine in addition to plagioclase and clinopyroxene occurs at Tang Mountain.

The trachyandesite at Tang Mountain does not appear to be related to subduction. The volcanic fields in the Takhakhdona Hill, at Indian Mountain, the Dulbi River, and the Yukon River are dominantly composed of felsic tuff, flow, and breccia, but the Takhakhdona Hills field also contains subordinate basalt, andesite, and dacite. Mafic, intermediate, and felsic rocks from the Takhakhdona Hills have arc-like trace-element signatures (Fig. 9), but felsic compositions predominate and the rocks are more than 300 km from the most inland part of the active Aleutian–Alaska Range arc. The mid-Tertiary rocks in interior Alaska erupted contemporaneously with the start of a major pulse of volcanism in the Aleutian–Alaska Range arc and the bend in the Hawaiian-Emperor seamount chain (Clague and others, 1975).

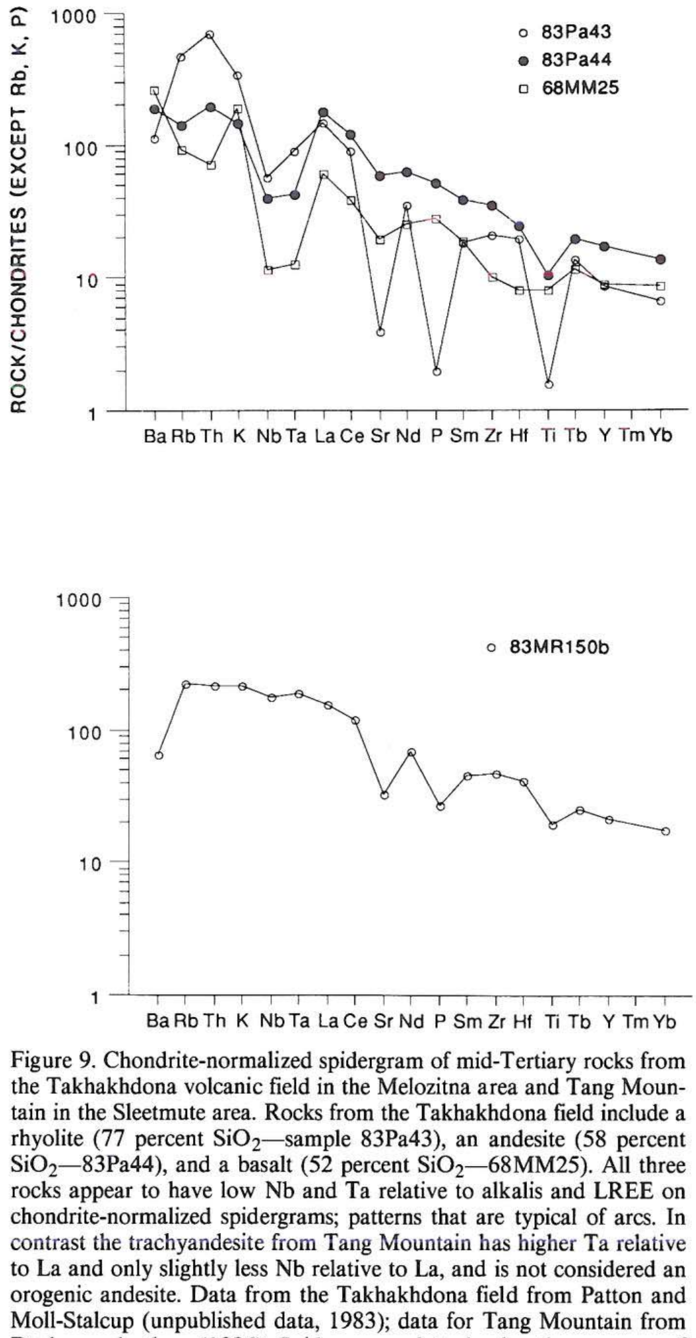


Figure 9. Chondrite-normalized spidergram of mid-Tertiary rocks from the Takhakhdona volcanic field in the Melozitna area and Tang Mountain in the Sleetmute area. Rocks from the Takhakhdona field include a rhyolite (77 percent SiO_2—sample 83Pa43), an andesite (58 percent SiO_2—83Pa44), and a basalt (52 percent SiO_2—68MM25). All three rocks appear to have low Nb and Ta relative to alkalis and LREE on chondrite-normalized spidergrams; patterns that are typical of arcs. In contrast the trachyandesite from Tang Mountain has higher Ta relative to La and only slightly less Nb relative to La, and is not considered an orogenic andesite. Data from the Takhakhdona field from Patton and Moll-Stalcup (unpublished data, 1983); data for Tang Mountain from Decker and others (1986). Spidergrams plotted using the program of Wheatley and Rock (1987).

Wallace and Engebretson (1984) also show a change from rapid northward-directed subduction of the Kula plate to slow northwest subduction of the Pacific plate at 43 Ma. The eruption of the volcanic rocks may be related to this change in the rate and angle of plate motion or to the switch from the Kula to the Pacific plate. Changes in angle of subduction may have resulted in movement along the many strike-slip faults in the area; however, the volcanic fields are not located on or near mapped faults, and their lack of deformation suggests that they have not experienced major movement. Also, paleomagnetic studies of Oligocene volcanic rocks in the Yukon River (Harris, 1985) and Lake Clark areas (Thrupp and Coe, 1986) suggest that the rocks have not rotated or moved latitudinally relative to North America since their formation.

Rocks of mid-Tertiary age may occur in at least two offshore basins. Eocene basalts having K/Ar ages of 40.7 ± 2 and 42.3 ± 10 Ma were found at the bottom of the Cape Espenberg and Nimiuk wells, drilled in the Kotzebue basin (Tolson, 1986). Poorly dated basalt flows or sills were also found near the bottom of wells drilled in Norton Sound basin and are thought to be middle to late Eocene (Kirschner, this volume). Both basins are extensional basins with horsts and grabens (Norton Sound) or graben and half-graben (Kotzebue) structures (Kirschner, this volume). Although no chemical data are available on these rocks, their occurrence at the bottom of offshore basins clearly indicates an origin in an extensional tectonic environment.

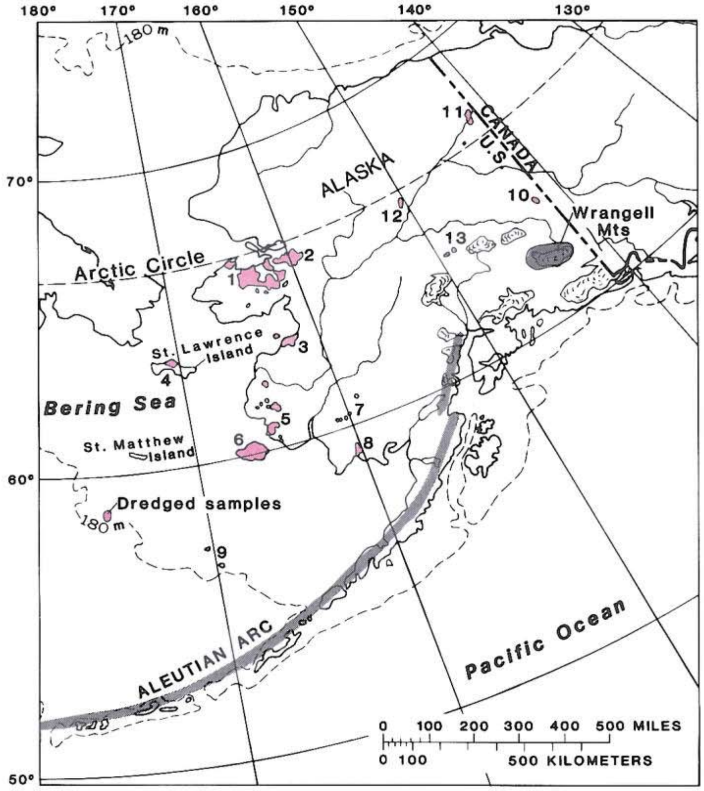


Figure 10. Location of late Cenozoic (0 to 6 Ma) volcanic fields in Alaska. 1, Imuruk Lake area; 2, Devil Mountain; 3, St. Michael volcanic field; 4, St. Lawrence Island; 5, Ingakslugwat volcanic field; 6, Nunivak Island; 7, Flat Top Mountain; 8, Togiak Basalt; 9, Pribilof Islands; 10, Prindle Volcano; 11, Porcupine-Black Rivers; 12, Ray Mountains; 13, Jumbo Dome (west) and Buzzard Creek (east). Red, chiefly basalt and basanite; shaded pattern, chiefly arc volcanic rocks. Dashed line marking 180-m water depth delineates the edge of the Bering Sea shelf.

LATE CENOZOIC VOLCANISM

Late Cenozoic volcanism in Alaska is dominated by calc-alkalic activity along the Aleutian arc and in the Wrangell Mountains and by contemporaneous alkalic and tholeiitic volcanism behind the arc in the Bering Sea region and easternmost interior Alaska (Fig. 10). The Aleutian arc has been active for at least the last 50 m.y. (Scholl and others, 1986), whereas most of the alkalic and tholeiitic Bering Sea basalts are restricted to the last 6 m.y.

Bering Sea region

The Bering Sea volcanic province consists of a number of large late Cenozoic basalt fields that occur in a vast region extending from St. Lawrence and the Pribilof Islands on the submerged Bering Sea shelf landward to the Seward Peninsula and Togiak River valley in western Alaska (Fig. 10). Most fields consist of a broad plain or shield composed of voluminous basalt flows overlain by steep cones and maars of undersaturated highly alkalic magma. Basaltic volcanism began as an isolated event about 28 to 26 m.y. ago with the eruption of the Kugruk Volcanics on the Seward Peninsula (Hopkins and others, 1963; Swanson and others, 1981). However, most of the volcanism in the Bering Sea region is much younger. Volcanism on Nunivak Island began 6 m.y. ago (Hoare and others, 1968), about the same time it resumed on the Seward Peninsula (5.8 Ma; Swanson and others, 1981). Most of the other fields began erupting in the Pliocene and Pleistocene.

On Nunivak Island, geologic mapping, paleomagnetic reversal stratigraphy, and K/Ar dating were used to determine the time and volume relations of volcanism (Hoare and others, 1968). The volcanic rocks range in age from 6 Ma to Holocene; the older series (3 to 6 Ma) underlies the western third of the island, and the younger series (0 to 1.7 Ma) covers the eastern two-thirds of the island.

Two suites occur on Nunivak Island: about 98 percent of the volcanic rocks form broad, thin pahoehoe flows of alkali basalt and subordinate tholeiite that make up 30 to 50 small shield volcanoes. The remaining 2 percent are basanites and nephelinites that form small, viscous flows, about 60 cinder cones, and ash deposits from four maar craters (J. M. Hoare, unpublished data, 1971). Subordinate eruptions of basanite or nephelinite commonly preceded and followed large eruptions of less alkalic basalt (J. M. Hoare, unpublished data, 1971). Analcime- or nephelinebearing basanite or nephelinite overlie the Cretaceous sedimentary basement rocks on Nunivak Island and, in turn, are overlain by less alkalic basalts (J. M. Hoare, unpublished data, 1971). The youngest volcanism produced 40 to 50 basanite cones and four maar craters, which erupted in the last 0.5 m.y. in the south-central part of the island (Hoare and others, 1968). The cones and craters are aligned approximately east-west along several parallel fractures in a belt about 40 km long and 12 km wide. The basanite and nephelinite contain abundant inclusions of lherzolite, layered gabbro, chromite, conglomerate, sandstone, and basalt, and megacrysts as much as 10 cm long of anorthoclase, augite, and kaersutite.

The late Cenozoic (0.24 to 1.5 Ma) volcanic shield in the Kookooligit Mountains on St. Lawrence Island covers 42 by 33 km, is at least 500 m thick, and overlies volcanic, plutonic, and sedimentary rocks of early Paleozoic to Tertiary age (Patton and Csejtey, 1980). About 95 to 97 percent of the volcanic rocks are alkali-olivine basalt and subordinate amounts of olivine tholeiite, and 3 to 5 percent are basanite and minor nephelinite (J. M. Hoare, unpublished data, 1981). Large fluid flows of alkali-olivine and olivine-tholeiite basalt erupted from many small craters (20 to 60 m in diameter) and from one or more larger craters (100 to 150 m in diameter) located in the central part of the field (J. M. Hoare, unpublished data, 1981). Many small basanite flows and 60 to 80 cinder cones are aligned along an east-west belt across the north-central part of the field. Most of the basanite flows and cones contain xenoliths of deformed peridotite and/or gabbro. Sparse xenoliths of granitic rock and siliceous tuff in basanite cones and flows have been found at three localities.

Widespread late Cenozoic volcanic fields cover abut 10,000 km^2 of the Seward Peninsula (Till and Dumoulin, this volume). The Imuruk Lake area was originally mapped by Hopkins (1963), who distinguished five volcanic formations on the basis of weathering, degree of frost brecciation, and thickness of wind-blown silt. K/Ar studies in the Imuruk Lake region document the five eruptive episodes: (1) 28 to 26 Ma, (2) 5.8 to 2.2 Ma, (3) 0.9 to 0.8 Ma, (4) late Pleistocene, and (5) Holocene (Swanson and others, 1981). These data indicate that the earliest eruptive episode occurred 20 m.y. before the onset of mafic alkalic volcanism elsewhere in the Bering Sea region. The Imuruk Lake volcanic field is composed dominantly of alkali-olivine basalt and subordinate olivine tholeiite, quartz tholeiite, and basanite erupted from small shield volcanoes, cinder cones, plugs, and maar craters. Xenolithic inclusions, which occur in alkalic basalt and basanite, consist dominantly of lherzolite and subordinate harzburgite, chromite, schist, and granite. Additional basalt fields on the Seward Peninsula include basanite, tephrite, and alkali olivine basalt from a 2.5 to 2.9-Ma field north of Teller on the margin of the Imuruk basin and one at Devil Mountain in the northernmost part of the Peninsula (S. Swanson and D. Turner, unpublished data, 1984).

The Pribilof Islands, located near the edge of the Bering Sea shelf, were also the site of late Cenozoic volcanism. Volcanism occurred on St. George, the northern island, between 2.2 and 1.6 Ma, and on St. Paul Island, located 70 km to the south, from 0.374 Ma to the present (Cox and others, 1966; Lee-Wong and others, 1979). Volcanism was active in the intervening time on a submarine ridge located between St. George and St. Paul Islands, where dredged whole-rock basalt samples yield ages of 0.774 and 0.836 Ma (Simpson and others, 1979). St. George Island consists chiefly of deeply dissected olivine tholeiite flows. Its topography is controlled by numerous east-west–trending normal faults. St. Paul Island consists of coalescing small volcanoes, each composed of a central cinder cone and a surrounding shield of lava flows composed of alkali-olivine basalt and basanite. Dredged samples from the submarine ridge are chiefly olivine tholeiite, subordinate alkali-olivine basalt, minor basanite, and nephelinite (Lee-Wong and others, 1979).

The Togiak Basalt in southwestern Alaska (location 8 on Fig. 10) consists of about 9 km^3 of tholeiitic and alkali-olivine basalt flows (0.76 Ma) overlain by a tuya, or table mountain, formed by a subglacial basaltic eruption (Hoare and Coonrad, 1978a, 1980). The tuya consists of palagonitized glassy tuff and pillow lava capped by glassy subaerial flows of alkali-olivine basalt that probably erupted during glacial advances more than 39,000 yr ago.

The Yukon Delta contains numerous small volcanic fields that consist of alkali-olivine basalt flows, erupted from low saucer-shaped cones, overlain by young steep-sided cones composed of basanite and nephelinite (Hoare and Condon, 1971a; J. M. Hoare, unpubished data, 1971). Olivine nephelinite ash, perhaps erupted from a maar crater in the Ingakslugwat Hills, contains abundant olivine gabbro and lherzolite nodules (Hoare and Condon, 1971a). Some of the young steep-sided cones are aligned west-northwest, indicating a probable fracture control (Hoare and Condon, 1971a).

A large volcanic field covering about 2,000 km^2 near St. Michael Island in southeastern Norton Sound consists chiefly of voluminous olivine tholeiite and alkali-olivine basalt flows, and basanite tuffs, cones, and maar craters. Some of the young cones and short flows, such as those at Crater Mountain, consist of basanite with lherzolite nodules; others, such as a recent lava flow southeast of Crater Mountain, consist of olivine tholeiite. Flows from the base of the St. Michael volcanic field give whole-rock ages of 3.25 and 2.80 Ma (D. L. Turner, written communication, 1986). The approximate age of flows in the St. Michael volcanic field and on the Yukon delta were determined by Hoare and Condon (1966, 1968, 1971a, b) and Hoare and Coonrad (1959, 1978a) using magnetic polarity and physiographic expression of the rocks. Their data indicate that the flows were erupted during both the Brunhes Normal- (0.7 Ma to the present) and Matuyama Reversed- (2.4 to 0.7 Ma) Polarity Chrons. A few highly dissected flows in these areas may be as old as Pliocene.

A small olivine basalt field at Flat Top Mountain east of the Kuskokwim delta (4.62 to 4.72 Ma; Decker and others, 1986) is presumed herein to be part of the Bering Sea province.

Petrogenesis. Much confusion over the composition of the Bering Sea volcanic rocks exists because one of the few published papers describes the rocks on Nunivak Island as chiefly tholeiitic basalt and subordinate, highly undersaturated alkalic basalt (Hoare and others, 1968), although alkali olivine basalt is the most common rock type (J. M. Hoare, unpublished data, 1971). More recent studies in the province have focused on the peridotite inclusions from Nunivak (Francis, 1976a, b, 1978; Menzies and Murthy, 1980a, b; Roden and Murthy, 1985; Roden and others, 1984), the tectonic stress orientation of the province (Nakamura and others, 1977, 1980; Nakamura and Uyeda, 1980), and the Sr and Nd isotopic composition of the inclusions and volcanic rocks (Mark, 1971; Von Drach and others, 1986). Most authors describe the rocks as "back-arc" basalt because of their location behind the Aleutian arc.

For this chapter, I examined 200 analyses from St. Lawrence, Nunivak, St. Michael, and Ingakslugwat (J. M. Hoare, unpublished data, 1967–1971), 36 from the Pribilof Islands (Lee-Wong and others, 1979), 3 of the Togiak Basalt (Hoare and Coonrad, 1980), and 19 from the Seward Peninsula (Swanson and Turner, unpublished data, 1981). Thin sections from Hoare's collections show fresh phenocrysts and groundmass minerals, including olivine, and almost all of the analyses have less than 1 percent total H_2O.

Volcanic rocks in most fields range from nephelinites having more than 25 percent normative nepheline to tholeiites having 15 percent normative hypersthene. Most of the fields are compositionally similar to the volcanic field on Nunivak. Alkaline olivine basalt and olivine tholeiite represent at least 95 percent of the volcanic rocks present in all the volcanic fields (J. M. Hoare, unpublished data, 1967–1972) and form flat-lying flows and shield volcanoes. About 2 to 3 percent of the rocks are highly alkalic undersaturated basanite and nephelinite, which form short, viscous flows, cones, and ash. Eruptions of small volumes of highly alkalic undersaturated magma generally preceded and postdated voluminous outpouring of alkali and tholeiitic basalt (J. M. Hoare, unpublished data, 1971).

Most of the volcanic rocks have a 100 $Mg/[Mg + Fe^{2+}]$ greater than 65, and many contain ultramafic mantle xenoliths, which suggest that they may be primary or near-primary melts of mantle peridotite that have experienced little or no residence time in shallow magma chamgers and rose relatively rapidly to the surface. Data from both the basanite-nephelinite suite and the basalt suite cluster on AFM diagrams, further supporting the general lack of differentiation in the suite. Rare hawaiite (100 $Mg/[Mg + Fe^{2+}]$ = 55 to 64) has been reported on St. Lawrence Island, from the St. Michael volcanic field, and in dredgings from the ridge between St. Paul and St. George Islands, but has not been reported from the other areas.

Both the alkali-olivine and tholeiitic basalts have phenocrysts of olivine, plagioclase, clinopyroxene, magnetite, and ilmenite; they are characterized by diktytaxitic textures. Hawaiites have less olivine; basanites lack plagioclase phenocrysts. Basanites have nepheline and analcime, and nephelinites have sodic pyroxene and nepheline in the groundmass mesotasis (Hoare and others, 1968). None of the samples examined in thin section contained modal hypersthene, but it has been reported in the Imuruk Volcanics from the Imuruk Lake area (Hopkins, 1963).

The basanites and nephelinites commonly contain megacrysts and/or xenoliths of peridotite, gabbro, or bedrock. The megacrysts consist of unzoned anorthoclase, clinopyroxene, and kaersutite, as much as 10 cm long (Hoare and others, 1968). Most of the megacrysts are deformed, showing kink bands and undulatory extinction, and most show reaction relations to their host basalt. Aluminous clinopyroxene, kaersutite, and feldspar are common megacrysts in alkalic basalts around the world (Irving, 1974). Experimental studies of megacrysts and their host basalts suggest that megacrysts of clinopyroxene and kaersutite are near-liquidus phases of the host basalt at high pressures (10 to 20 kb). In contrast, experimental work suggests that anorthoclase is never a liquidus phase in a basalt or basanite at any pressure, and they therefore are generally thought to have precipitated from more evolved magmas, which later mixed with the host basalt (Irving and Frey, 1984). The lack of differentiated magmas in the Bering Sea basalt province, however, makes this mechanism unlikely in these magmas. H. Wilshire (oral communication, 1985) believes that anorthoclase megacrysts in the Mojave Desert, California, formed in mantle veins due to several generations of partial melting. The anorthoclase megacrysts in the Bering Sea basalts may have formed in a similar manner and were disaggregated during their rise to the surface.

The most abundant xenoliths, 75 percent of Nunivak's xenolith population (Francis, 1976a), are lherzolite nodules composed of olivine, enstatite, clinopyroxene, and spinel. Less than 1 percent of the lherzolite nodules on Nunivak contain chromian pargasitic amphibole, but about 50 percent contain zones of fine-grained diopside, olivine, spinel, and Al-rich glass, which Francis (1976a) interprets as relicts of melted amphibole. Red-brown chromian mica occurs between the amphibole and included spinel in some samples. Francis (1976a) believes that the spinel lherzolite xenoliths are accidental fragments of upper mantle and that amphibole formed during a mantle metasomatic event accompanied by infiltration of aqueous fluids enriched in alkalis and incompatible elements. He further suggests that the metasomatism predates entrainment of these nodules in the alkali basalt.

Other common xenoliths include corona-bearing pyroxene granulites (9 percent of Nunivak's xenolith population), which range from plagioclase to olivine dominated (Francis, 1976b). The reaction of olivine and plagioclase to clinopyroxene-spinel symplectite and aluminus orthopyroxene suggests that the xenoliths last equilibrated at 950°C under at least 9 kbar pressure. Francis (1976b) interprets the xenoliths as fragments of the base of the crust, and proposes that the reaction took place in the corona structures in response to crustal thickening of the Bering Sea shelf from thin oceanic crust (10 km) in the early Mesozoic to thicker crust (about 30 km) in the Quaternary.

Other reported xenoliths include bedrock of obvious crustal origin and dunite, harzburgite, chromite, gabbro, and amphibole-bearing pyroxenite of less certain origin (Hoare and others, 1968;

Francis, 1978). Lithologies of the bedrock xenoliths vary depending on the location of the volcanic field. At least some at each locality consist of fragments of underlying basalt flows.

The Bering Sea province is characterized by high alkali and low silica content and ranges in composition from nephelinite to basanite through alkali-olivine basalt to olivine tholeiite and tholeiite. Total alkalis decrease with increasing SiO_2 (Fig. 11) as in the Hawaiian suites (Clague and Frey, 1982; Frey and Clague, 1983). But, Bering Sea basalts have lower CaO than Hawaiian lavas, which result in greater silica saturation at a given total alkali content. Figure 11 shows the dividing line for alkalic and tholeiitic rocks in the Bering Sea province and the line of silica saturation, as defined by MacDonald and Katsura (1964) for the Hawaiian Islands.

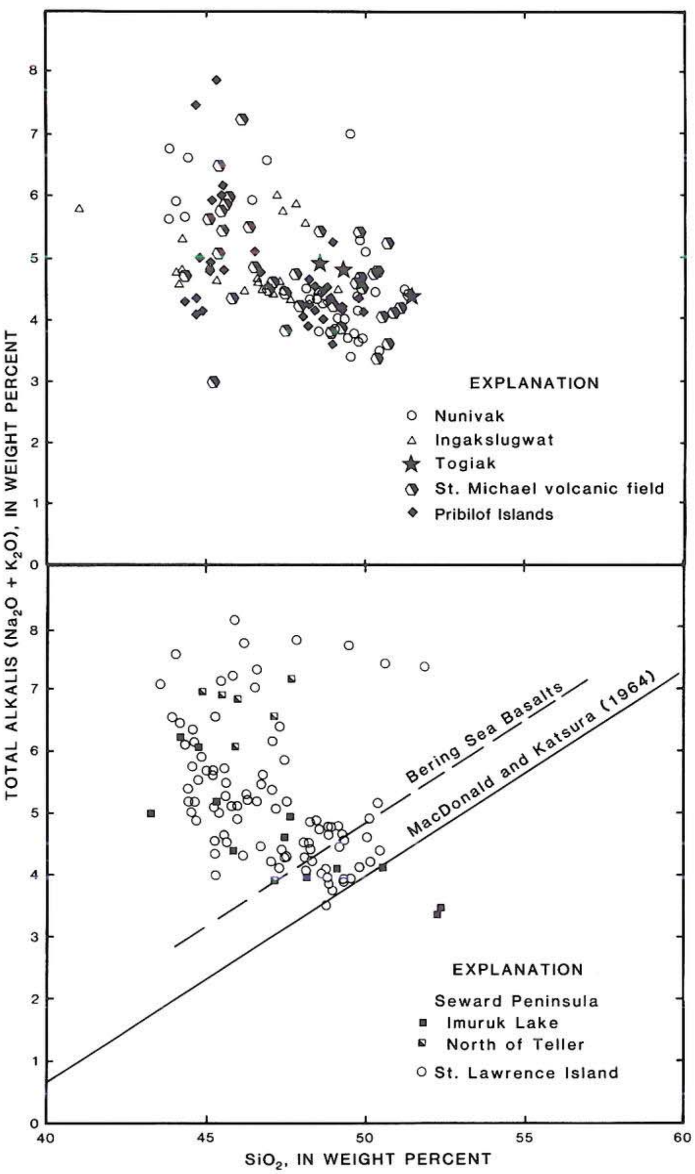


Figure 11. Plot of total alkalies versus SiO_2 for Bering Sea basalts. Lines divide silica-saturated and silica-undersaturated rocks on Hawaii and in Bering Sea basalts. Data from J. M. Hoare (unpublished data, 1971), S. Swanson and D. Turner (unpublished data, 1985), and Lee-Wong and others (1979).

REE data from Nunivak (Roden, 1982), the Pribilof Islands (Kay, 1977; Florence Lee-Wong, unpublished data, 1986), and St. Michael volcanic field (E. J. Moll and W. W. Patton, Jr., unpublished data, 1987) show that lavas from these fields are LREE enriched. LREE are correlated with alkalinity: nephelinites have 40 ppm La and tholeiites have about 10 ppm La.

P_2O_5, Rb, Sr, Ba, K_2O, and Na_2O all decrease with increasing silica and correlate positively with each other (J. M. Hoare, unpublished data, 1967–1971; Mark, 1971). These trends cannot be due to crystal fractionation of any phenocryst commonly found in the basanites or basalts. Studies of suites of similar composition (Frey and others, 1978; Clague and Frey, 1982) have shown that basalt to nephelinite to melilite suites formed by decreasing degrees of partial melting of a garnet peridotite source. By analogy, this suggests that Bering Sea nephelinites, which have the highest Rb, Sr, Ba, K, Na, and P and the lowest SiO_2, originated by the smallest degree of partial melting; and that tholeiites, which have the lowest alkalis and highest SiO_2, originated by the greatest degree of partial melting. Experimental petrologists have suggested that strongly silica-undersaturated magmas form from a peridotite mantle rich in carbon (Wyllie and Huang, 1976; Eggler and Holloway, 1977; Eggler, 1978). I examined P and K data from more than 200 major-element analyses of rocks from St. Lawrence Island to estimate the range of partial melting required by this volcanic field using the method of Clague and Frey (1982). For the olivine tholeiite to nephelinite series, K_2O varies from 0.4 to 2.2 percent and P_2O_5 varies from 0.22 to 0.71 percent. K content has the widest range, which suggests that it is the most incompatible major element. If K behaves as a totally incompatible element (D = 0) during partial melting, and no fractional crystallization occurs, its compositional range requires that the degree of partial melting vary by a factor of at least 5. Trace elements are probably more incompatible than major elements. Trace element data are not available for most of the Bering Sea basalt fields, but Rb data on a small suite of samples from Nunivak Island vary from 5.8 to 64.4 ppm (Mark, 1971), a factor of 11, over the range olivine tholeiite to nephelinite. A factor of 11 corresponds to a melting interval of at least 11 percent or 1 to 11 percent, 2 to 22 percent. However, as discussed below, Sr isotope data on the Bering Sea magmas suggest they have not originated in a mantle that has isotopically homogeneous $^{87}Sr/^{86}Sr$. The source for the nephelinites has lower $^{87}Sr/^{86}Sr$, and therefore probably lower Rb/Sr, than the source for the less alkalic basalts, which suggests that the melt interval is probably larger. Frey and others (1978) suggest that 4 to 25 percent melting produced a compositional range from olivine melilite to quartz tholeiite in the Tertiary to Holocene basalts of Victoria, Australia and Tasmania. Although I cannot rigorously constrain the degree of partial melting for the Nunivak Island suite, the data suggest that the nephelinites form by small amounts of partial melting, probably on the order of 1 to 3 percent, and the tholeiites formed by larger amounts of melting, on the order of 11 to 33 percent.

Three isotopic studies have been done on the Bering Sea province, and a summary of the reported data is shown in Figure 12. In the first study, Mark (1971) analyzed the Sr isotopic composition of more than 24 samples, ranging from nephelinite to tholeiite, from Nunivak Island and of a few samples from St. Lawrence and St. Michael Islands, Ingakslugwat Hills, and the Pribilof Islands. He found that $^{87}Sr/^{86}Sr$ = 0.7026 to 0.7033 and decreased with increasing alkalinity and decreasing silica saturation in the Nunivak samples. Nine basanites have $^{87}Sr/^{86}Sr$ of 0.70286 ± 0.00018, and 15 alkali-olivine and tholeiitic basalts have $^{87}Sr/^{86}Sr$ of 0.70311 ± 0.00013. Samples from the Pribilofs, Ingakslugwat, and St. Michael fall within the range of Sr isotope ratios given for Nunivak. $^{87}Sr/^{86}Sr$ on samples from St. Lawrence Island, which overlies Paleozoic sedimentary rocks, are higher, ranging from 0.7036 to 0.7039, and also decrease with increasing alkalinity.

Menzies and Murthy (1980a, b) studied the Sr and Nd isotopic composition of basalts, kaersutite megacrysts, and paragasite from lherzolite nodules from Nunivak in the second isotopic study. They report Sr isotope data for volcanic rocks, ranging from nephelinites to olivine tholeiites, similar to values reported by Mark in 1971 ($^{87}Sr/^{86}Sr$ = 0.70251 to 0.70330 and $^{143}Nd/^{144}Nd$ ranging from 0.51289 to 0.51304). In contrast to Sr, the Nd isotopes do not correlate with alkalinity. The nodules and megacrysts have $^{87}Sr/^{86}Sr$ ranging from 0.7027 to 0.7033, which suggests that the mantle under Nunivak is locally inhomogeneous in $^{87}Sr/^{86}Sr$. Coexisting pargasite and nodules have identical isotopic composition within analytical uncertainty. The Nunivak data plot on a $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ diagram in the field where MORB (mid-ocean-ridge basalt) and OIB (oceanic-island basalt) overlap (Menzies and Murthy, 1980a, b; Roden and others, 1984) but are LREE enriched (Roden, 1982). Thus, the low-Nd isotopic composition of the basalts and nodules requires a time-integrated LREE—depleted source for the basalts, but all the basalts, even the tholeiites, are LREE enriched (Fig. 13). Menzies and Murthy (1980a) suggest that the LREE and other incompatible elements were enriched in the source region by relatively recent (within the last 200 m.y.) mantle metasomatism and that the range in Sr isotopic composition can be explained by local inhomogeneities in Rb/Sr that developed during the metasomatic event and resulted in small variations in $^{87}Sr/^{86}Sr$ over time.

The third isotope study (von Drach and others, 1986) focused on the Nd and Sr isotopic composition of the Aleutian Islands but also reported data from Nunivak, St. George, and St. Lawrence Islands. Data for Nunivak and St. George are identical to the previously published results on Nunivak (Menzies and Murthy, 1980b) and plot on the $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ dia-

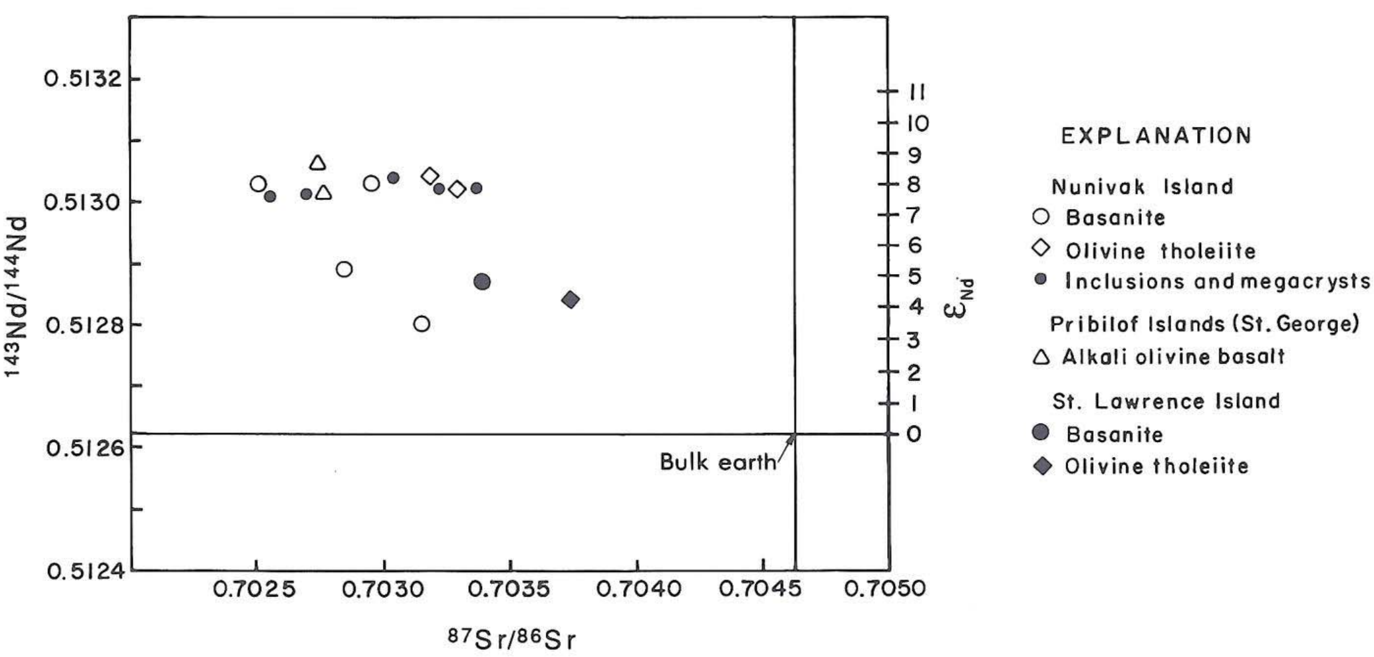


Figure 12. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data for Bering Sea basalts. Data from Menzies and Murthy (1980a), von Drach and others (1986), and Roden (1982). Rocks from St. George in the Pribilof Islands and Nunivak Island plot in the field where values for MORB (mid-ocean-ridge basalt) and oceanic island basalt overlap. Analyses of samples from St. Lawrence Island plot closer to bulk-earth compositions. Bulk-earth values from Allegre and others (1984).

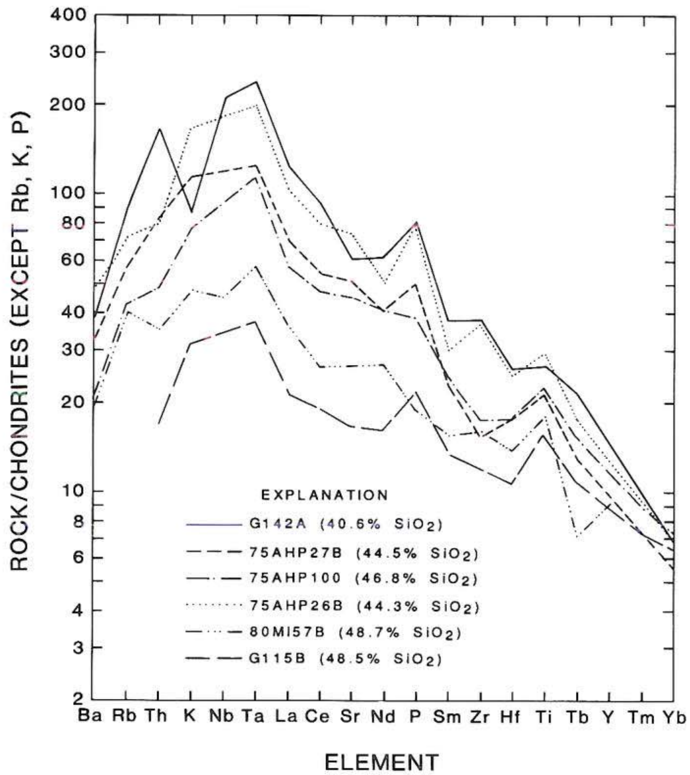


Figure 13. Chondrite-normalized spidergrams for volcanic rocks from the St. Michael volcanic field (80ML57B) and the Pribilof Islands (P26B, G142A, P27B, HP100, and G115B). Data from E. J. Moll-Stalcup and W. W. Patton, Jr. (unpublished data, 1980–1981), and F. Lee-Wong (unpublished data, 1981). The rocks having the highest alkalies and LREE are nephelinites; those having the lowest are tholeiites. Note the positive Nb-Ta anomaly.

gram in the field where MORB and OIB overlap. $^{143}Nd/^{144}Nd$ is 0.5133 ± 0.0002 and $^{87}Sr/^{86}Sr$ is 0.7025 to 0.7033 for six of the seven samples from both Nunivak and St George. Rocks from St. Lawrence Island have significantly higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ and plot along the mantle array within the field for oceanic basalts (Fig. 12).

Data from all three studies suggest that volcanic rocks from Nunivak, the Pribilofs, Ingakslugwat, and St. Michael are isotopically similar and plot in the field where MORB and OIB overlap. $^{143}Nd/^{144}Nd$ values are about 0.5132, and $^{87}Sr/^{86}Sr$ ranges from 0.7025 to 0.7033 for all the analyzed fields except St. Lawrence Island, which has a basement composed of rocks at least as old as middle Paleozoic, and has higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than the other volcanic fields (Fig. 12). In all the fields where data are sufficient, $^{87}Sr/^{86}Sr$ appears to be negatively correlated with silica undersaturation and alkalinity. Hawaiian volcanic rocks on Oahu show a similar trend—the Honolulu Group, which is composed of undersaturated alkalic rocks, has lower $^{87}Sr/^{86}Sr$ (0.70331) than the underlying tholeiitic shield (0.70370) (Lanphere and others, 1980; Lanphere and Dalrymple, 1980; Clague and Frey, 1982). The source of the St. Lawrence Island magmas is either mantle that has higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than the other volcanic fields (continental lithospheric mantle?) or crustally contaminated isotopically similar mantle. Inclusions of sialic rock have been reported in highly alkalic magmas on St. Lawrence Island (Patton and Csejtey, 1980). However, the primitive composition of the magmas, which suggests little differentiation and thus little or no residence time in shallow magma chambers, argues against the crustal contamination hypothesis. Although it is possible that crustal contamination may be responsible for the range in $^{87}Sr/^{86}Sr$ within individual volcanic fields, it is not required because a similar range in $^{87}Sr/^{86}Sr$ is found in the mantle, as evidenced from xenolith studies from Nunivak (Menzies and Murthy, 1980b). The proposed metasomatic event that enriched the mantle under the Bering Sea and western Alaska in K, LREE, and P probably occurred within the last 200 m.y., as suggested by Menzies and Murthy (1980b), but was not synchronous with the alkalic volcanism, as suggested by Roden and others (1984). Consequent metasomatism as suggested by Roden and others (1984) does not account for the range in $^{87}Sr/^{86}Sr$ in the basalts nor does it explain how large volumes of LREE-enriched magmas (including tholeiites) could form from a LREE-depleted mantle that had a small volume of LREE-enriched veins. It seems more likely that a separate metasomatic event, perhaps related to earlier subduction in the Neocomian or Late Cretaceous and early Tertiary, was responsible for the enrichment.

The Ingakslugwat Hills, Nunivak Island, and St. Michael Islands lie within the Yukon-Koyukuk basin, and the Pribilof Islands may lie within an offshore extension of this basin. The Yukon-Koyukuk basin is thought to be a Mesozoic island arc that collided with western Alaska in mid-Cretaceous time (Patton and Box, 1989). Studies of crustal xenoliths included in the basaltic flows indicate that sialic rocks of pre-Cretaceous age do not occur in the St. Michael, Nunivak, or Ingakslugwat volcanic fields (J. M. Hoare, unpublished data, 1981). The lack of pre-Cretaceous sialic inclusions suggests that Paleozoic strata are not present beneath these areas and further suggests that the lithosphere under the basin might have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ than the lithosphere under older, long-lived continental areas such as St. Lawrence Island.

In summary, the Bering Sea basalt suites of nephelinite to tholeiite probably originated by increasing degrees of partial melting of a peridotite mantle rich in carbon. Most of the magmas rose quickly to the surface, and few, if any, were significantly differentiated. The basanites and nephelinites originated in a source having lower $^{87}Sr/^{86}Sr$ than the source of the less alkalic basalts. The small range in $^{87}Sr/^{86}Sr$ is probably due to mantle metasomatism that enriched the source area in K, LREE, Sr, Rb, and P within the last 200 m.y. (Menzies and Murthy, 1980b). Furthermore, this metasomatism may be related to previous subduction events in western Alaska during the Neocomian or Late Cretaceous and early Tertiary. The volcanic rocks on St. Lawrence Island have more radiogenic $^{87}Sr/^{86}Sr$ and less radiogenic

$^{143}Nd/^{144}Nd$ than volcanic rocks from the other fields and suggest the presence of more enriched mantle under St. Lawrence Island—possibly continental lithospheric mantle. The correlation between exposed crustal type and Sr and Nd isotope composition can be explained by tectonic models for western Alaska that require younger and more mafic crust beneath the Yukon-Koyukuk province than the crust under the surrounding metamorphic borderlands and St. Lawrence Island.

Eastern and central interior Alaska

Several small, isolated basaltic volcanoes occur in easternmost Alaska, between the Fortymile and Tanana Rivers. The cones and associated flows are undated but apparently are young, as evidenced by their well-preserved volcanic morphology. The best-preserved and probably youngest cone is Prindle volcano, a small cinder cone that was the source of a narrow basanite lava flow more than 10 km long (Foster and others, 1966). The cone and adjacent flow contain abundant inclusions of harzburgite, wehrlite, lherzolie, pyroxenite, and granulite-facies schist. Prindle volcano is undated but underlies the (informally named) White River ash bed, which was dated by ^{14}C methods at approximately 1,900 B.P. (Lerbekmo and Campbell, 1969).

Large volumes of olivine basalt flows, as much as 100 m thick, are exposed in fault blocks near the Porcupine and Black Rivers (Brosgé and Reiser, 1969). The flows are considered to be Tertiary or Quaternary because of their youthful appearance. One chemical analysis, of an alkali-olivine basalt, is available from flows along the Black River (Brabb and Hamachi, 1977).

Miscellaneous isolated volcanic rocks of late Cenozoic age also occur in central Alaska. A small, isolated maar volcano composed of olivine basalt erupted 3,000 years ago at Buzzard Creek on the north side of the Alaska Range (Albanese, 1980). Flat-lying olivine basalt flows cover approximately 100 km^2 of north-central Alaska between the Yukon and upper Koyukuk Rivers, about 125 km northeast of the town of Tanana. These rocks are undated, but their lack of deformation suggests they are late Tertiary or Quaternary in age (Patton and Miller, 1973).

The few available analyses of volcanic rocks in central and eastern Alaska indicate that the rocks are compositionally similar to Bering Sea basalts. Alkalic basalts in the Porcupine and Yukon-Tanana upland area are located north of arc volcanoes in the Wrangell Mountains (Fig. 10). By analogy with Bering Sea basalts, these magmas probably represent regional extension behind the present arc. Cones and flows of olivine basalt, some of which contain ultramafic inclusions, also occur in a south-trending regional belt that extends from eastern Alaska into the Yukon Territory and continues down along the western North American continental margin through British Columbia (Foster and others, 1966; Sinclair and others, 1978).

Jumbo Dome, the only occurrence of Quaternary (0.80 to 2.8 Ma) orogenic andesite in interior Alaska, occurs about 10 km southwest of the maar volcano at Buzzard Creek (Fig. 10; Albanese, 1980). The hornblende andesite dome is probably related to subduction under this area, making it the only Quaternary occurrence of arc volcanism in the 300-km-wide magmatic gap between Mount Spurr, at the northeast end of the Aleutian arc, and the Wrangell Mountains.

Late Cenozoic tectonic implications

Bering Sea basalts have compositions similar to suites found in a variety of tectonic environments, including oceanic islands (Hawaii: Clague and Frey, 1982; Frey and Clague, 1983), stable continents associated with regional faulting (southern and eastern Australia: Irving, 1974; Frey and others, 1978; and the western U.S.: Menzies and others, 1987), continental rifts (east Africa: King, 1970), and behind volcanic arcs a great distance from the arc (China and Korea: Nakamura and others, 1985). The locations of the various volcanic fields do not define a narrow volcanic belt, a rift axis or a hot-spot trend. Most recent authors (Nakamura and others, 1977; von Drach and others, 1986) have labeled the Bering Sea basalts as back-arc basalts, although they do not constitute a classic back arc characterized by a spreading rift axis or by high heat flow (Marshall, 1978; Smirnov and Sugrobov, 1979a, b), nor do they have typical back-arc compositions, which usually range from N-MORB to arc tholeiite (Saunders and Tarney, 1984; Hawkins and Melchoir, 1985). Turner and others (1981) suggest that the basalts on the Seward Peninsula are related to an interconnected system of rifts and transform faults. Major- and trace-element data suggest that the Bering Sea basalts came from a source similar to oceanic island basalts. Trace-element ratios and isotopic compositions of the Bering Sea basalts are similar to Hawaiian volcanic rocks and different from N-MORB (Table 3). The Bering Sea volcanic fields, however, are not aligned along the trend of a hot spot. Chondrite-normalized multi-element diagrams show that, unlike arc basalts, Bering Sea basalts have positive Nb and Ta anomalies (Fig. 13) and, therefore, have a different source than the Aleutian arc.

Many of the voluminous basalt fields are located on or near strike-slip or normal faults, and fault displacements suggest that at least some of the faulting began while volcanism was still active. The Togiak Basalt is located in a north-northeast–trending graben (Hoare and Coonrad, 1980; Globerman, 1985). Late Pliocene volcanic rocks on St. George Island in the Pribilofs are cut by numerous normal faults, most of which trend approximately east-northeast (Hopkins, 1976). Several of the Yukon delta volcanic fields are located along a trace of the Anvik fault, and the volcanic field near St. Michael Island is probably intersected by a trace of a Kaltag fault splay (W. W. Patton, Jr., oral communication, 1984). Young volcanic cones are aligned approximately east-west, apparently defining a fracture or fault in the St. Lawrence, Nunivak, and St. Michael volcanic fields, and in a small field north of Aropuk Lake on the Yukon delta. Late Cenozoic volcanism in the Seward Peninsula is associated with transform faulting, geothermal anomalies, large late Tertiary grabens, and high levels of seismicity in the central Seward Peninsula (Turner and Forbes, 1980).

TABLE 3. COMPARISON OF SELECTED TRACE-ELEMENT RATIOS FOR A BERING SEA THOLEIITE WITH A HAWAIIAN THOLEIITE AND N-MORB

	Bering Sea basalts*	Hawaii†	Average N-MORB§
P_2O_5/Ce	87.0	81.3	0.02
Rb/Sr	0.044	0.031	0.008
K/Rb	409	432	1,060
Zr/Hf	46.4	45 ± 4	33.5
Hf/Ta	2.44	1.35	15.45
Th/La	0.125	0.091	0.065
Th/Ce	0.065	0.047	0.021
Th/Sm	0.47	0.39	0.063
Th/Nd	0.088	0.094	0.023
Sr/Th	214	246	660
Ba/Th	88.7	165.0	60.0
Sr/Ba	2.4	1.5	11.0
Ba/La	11.1	14.9	3.9
Ba/Ce	5.8	7.6	1.3
Zr/Ta	113.0	60.0	518.0
Sr/Ce	14.0	11.3	13.9

*St. Michael volcanic field (80ML57b).
†Clague and Frey (1982).
§Wood (1979).

The distribution of active faults and monogenetic cones in late Quaternary volcanic fields on St. Lawrence, St. Michael, Ingakslugwat, Nunivak, the Pribilofs, and the Seward Peninsula were used by Nakamura (Nakamura and others, 1977; Nakamura and Uyeda, 1980; Nakamura and others, 1980) to define the tectonic stress field in the Bering Sea region in the late Quaternary. Cones on most of the volcanic fields are aligned east-west, corresponding to east-west maximum horizontal compression. Maximum horizontal compression in the Aleutian arc is oriented north-south, perpendicular to the trench. The axis of maximum horizontal compression (MHC) can represent either the intermediate stress axis or the maximum stress axis. Nakamura uses a presumed tectonic environment of the volcanism to interpret the MHC in the Bering Sea region as representing north-south extension and the MHC in the arc as representing north-south compression.

Holocene surface faults (Hudson and Plafker, 1978; Plafker and others, this volume, Plate 12) and focal-mechanism solutions for earthquakes on the Seward Peninsula and adjacent northwestern Alaska show dominantly normal fault movement with extension in the northwest or northeast directions (Biswas and others, 1986). Biswas and others (1986) classify all of western Alaska and the Bering Sea shelf as an area of "tensional stress regime." However, they provide no mechanisms for western Alaska south of the Seward Peninsula area or for the Bering Sea shelf.

In late Cenozoic time the Bering Sea shelf was located in the vicinity of the Eurasian, North American, and Pacific plates. The shelf was probably part of the North American plate, and the plate boundary between Eurasia and North America was located to the west of the Bering Sea shelf in eastern Siberia (Zonenshain and others, 1984). Harbert and others (1987) suggest slight convergence between Alaska and Eurasia in a north to northeast direction from 37 to 0 Ma in the Bering Sea region, based on spreading patterns in the North Atlantic. North to northeast convergence contradicts Nakamura and Biswas's studies and suggests that compressive stress from convergence between the North American and Eurasian plates was localized along the plate boundary in Siberia and did not affect the Bering Sea shelf. Therefore, plate motion between the North American and Eurasian plates does not appear to be responsible for volcanism on the Bering Sea shelf.

In the Bering Sea region, motion between the North American and Pacific plates was dominated by north-directed subduction of the Pacific plate along the Aleutian trench for at least the past 50 m.y. None of the Bering Sea basalts, not even those from the Pribilof Islands, only 550 km from the trench, have the Nb-Ta depletions characteristic of arc magmas. Neither do they occur along a rift axis, nor do they have typical back-arc compositions. However, they were erupted in a broad extensional environment located behind the Aleutian arc. Thus, although the rocks do not constitute a classic back arc, the occurrence of the tholeiitic and alkalic basalt in the Bering Sea region behind the Aleutian arc and in east-central Alaska behind the Wrangell Mountains volcanoes suggests that they represent a broad zone of regional extension behind the arc. Alkaline basalts that lack Nb-Ta anomalies occur behind the Japanese arc in Korea and China (Nakamura and others, 1985) and this occurrence may be similar to that of the Bering Sea basalts.

Voluminous eruptions of Bering Sea basalts began at 6 Ma, contemporaneous with small changes in Pacific plate motion (Barron, 1986; Cox and Engebretson, 1985) and the start of a major pulse in volcanic activity in the Aleutian arc that continues to the present. The timing of eruptions in the Bering Sea region may be related to the change in the angle of Pacific plate motion at 6 Ma, or it may possibly represent the time necessary to heat the back-arc region before volcanism began.

SUMMARY AND CONCLUSIONS

The Alaska Range–Talkeetna Mountains, Kuskokwim Mountains, and Yukon-Kanuti belts constitute an anomalously wide volcanic arc that was active during the Late Cretaceous and early Tertiary. The arc was narrower, consisting of the Alaska Range–Talkeetna Mountains and Kuskokwim Mountains belts from 75 to 66 Ma and broadened considerably to include the Yukon-Kanuti belt from 65 to 56 Ma. Plate motion models predict rapid north-northeast–directed subduction of the Kula plate under southern Alaska between 75 and 56 Ma (Engebretson and others, 1982). The angle of convergence between Paleocene plate motions and the present continental margin and three parallel magmatic belts is too small to generate arc magmatism (Wallace and Engebretson, 1984; Gill, 1981). This enigma is resolved by paleomagnetic models that suggest that western Alaska has been rotated 30 to 55 degrees counterclockwise since the Paleocene (Globerman and Coe, 1984; Hillhouse and Coe, this volume).

Assuming that models for counterclockwise rotation of western Alaska are correct, the continental margin of southern Alaska, which now has a tightly curved S-shape, may have had a more open S-shape in the Late Cretaceous and early Tertiary. This configuration places St. Matthew Island close to the trench in Paleocene time, which is consistent with its low K contents and tentative correlation with the Alaska Range–Talkeetna Mountains belt. Unrotating western Alaska also places the continental margin and three magmatic belts approximately east-west in Paleocene time—orthogonal to the direction of subduction. Compression between Alaska and Eurasia related to opening in the North Atlantic was probably responsible for flexure of the southern continental margin into its present tight S-curve. This bending is proably responsible for the post-Paleocene counterclockwise rotation of western Alaska.

At about 56 Ma, the trench jumped away from the continental margin to its present position, and formation of the Aleutian ridge began (Scholl and others, 1986). Paleomagnetic data on Paleocene and Oligocene volcanic rocks suggest that rotation of western Alaska occurred between 56 and 43 Ma (Thrupp and Coe, 1986; Harris, 1985). Between 56 and 43 Ma, Engebretson and others (1982) show rapid north-directed subduction under southern Alaska. Subduction-related volcanic rocks between 56 and 48 m.y. old are restricted to the hinge line of the oroclinal bend (Arkose Ridge Formation and Talkeetna Mountains volcanic rocks), which may have been more orthogonal to the plate motion than the rotated (or rotating?) southwestern continental margin in the Eocene.

Mid-Tertiary volcanism in interior Alaska is chiefly felsic and appears to be related to regional extension or movement along strike-slip faults. This volcanism occurred at 40 ± 3 Ma, coincident with a change in the angle of Pacific plate motion at 43 Ma and the start of a peak in magmatic activity in the Aleutian arc that occurred between 40 and 30 Ma.

Bering Sea basalts were erupted in a broad extensional environment behind the Aleutian arc, but are not a classic back arc. Eruptions of the basalts, which started at about 6 Ma, are contemporaneous with changes in Pacific plate motion and the beginning of a major eruptive pulse in the Aleutian arc. Bering Sea basalts originated in a mantle source similar to that for oceanic island basalts. The source of the magmas had been previously metasomatized by the addition of K, P, REE, and Ti. This metasomatic event occurred within the last 200 m.y. (Menzies and Murthy, 1980b), probably during the widespread Early Cretaceous, or Late Cretaceous and early Tertiary subduction events.

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