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The Nature of the Crust in the Yukon-Koyukuk Province as Inferred From the Chemical and Isotopic Composition of Five Late Cretaceous to Early Tertiary Volcanic Fields in Western Alaska

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Late Cretaceous and early Tertiary volcanic and plutonic rocks in western Alaska comprise a vast magmatic province extending from the Alaska Range north to the Arctic Circle, south to Bristol Bay, and west to the Bering Sea Shelf. The chemical and isotopic composition of five of these Late Cretaceous to early Tertiary volcanic fields in the north central part of this province were studied to determine if Paleozoic or older continental crust underlies the Yukon-Koyukuk province. Three of the fields, the Blackburn Hills, Yukon River, and Kanuti, occur within the Yukon-Koyukuk province and two, the Sischu and Nowitna, overlie bordering Precambrian and Paleozoic metamorphic terranes to the southeast. High initial $^{87}Sr/^{86}Sr$ of 0.7075–0.7079 and moderate initial $^{143}Nd/^{144}Nd$ of 0.51244–0.51247 of rhyolite, dacite, and high-silica andesite of the Sischu volcanic field indicate that the magmas have interacted with the underlying Paleozoic or older continental crust. The relatively limited variation of isotopic (initial $^{87}Sr/^{86}Sr$ = 0.7044–0.7051; initial $^{143}Nd/^{144}Nd$ = 0.51256–0.51257) and elemental compositions of andesites from the Nowitna field can be accounted for by assimilation of small amounts of Paleozoic or older continental crust during crystal fractionation of andesite parent magmas at crustal levels. The Blackburn Hills field, which consists of medium-K basalt, andesite, and rhyolite intruded by a small granitic pluton, has a large range in initial $^{87}Sr/^{86}Sr$ and initial $^{143}Nd/^{144}Nd$ that plot in the field for 60 Ma mantle, from near mid-ocean ridge basalts to near "bulk-earth" compositions (initial $^{87}Sr/^{86}Sr$ = 0.7033–0.7052; initial $^{143}Nd/^{144}Nd$ = 0.51253–0.51290). Andesites and basalts from the Blackburn Hills are divided into two group on the basis of rare earth element (REE) and isotopic composition. Isotopic variation in the more primitive group 1 is best explained by assimilation of the lower crust of the Jurassic to Early Cretaceous Koyukuk terrane by mantle-derived basalts during crystal fractionation, though part of the isotopic variation may be due to metasomatism of an oceanic island basalt type mantle source by fluids derived from subducted sediments. Group 2 andesites from the Blackburn Hills have lower heavy REE abundances and more enriched isotopic compositions. These group 2 andesites and dacites from the Kanuti field, which have $(^{87}Sr/^{86}Sr)i$ = 0.7043–0.7048 and $(^{143}Nd/^{144}Nd)i$ = 0.51248–0.51267, appear to have formed by partial melting of the lower crust of the Koyukuk terrane. The Yukon River field consists of basalt, andesite, dacite, and rhyolite having $(^{87}Sr/^{86}Sr)i$ = 0.7037–0.7051 and $(^{143}Nd/^{144}Nd)i$ = 0.51266–0.51280; its isotopic composition does not require the presence of Paleozoic or older continental crust under the volcanic field and may have formed by interaction between mantle-derived melts and the oceanic Angayucham/Tozitna or island arc Koyukuk terrane. Most of the intrusive rocks and rhyolite domes from the Blackburn Hills volcanic field have $(^{87}Sr/^{86}Sr)i$ = 0.7038–0.7041 and dacites from the Kanuti volcanic field have $(^{87}Sr/^{86}Sr)i$ = 0.7043–0.7048. Thus little or no old continental crust was involved in the genesis of the Late Cretaceous and early Tertiary rocks and therefore probably does not extend beneath this part of the Yukon-Koyukuk province. However, the ultimate source of the small volumes of enriched shoshonitic andesite ($^{87}Sr/^{86}Sr$ = 0.7075, $^{143}Nd/^{144}Nd$ = 0.5125) erupted at 118 Ma in the Yukon-Koyukuk province may be continental lithosphere, which may have been thrust under this part of the Yukon-Koyukuk province during arc-continent collision in the Early Cretaceous.

INTRODUCTION TO THE PROBLEM

Late Cretaceous and early Tertiary (75–56 Ma) magmatism occurred in a vast region of western Alaska, extending from the Alaska Range north to the Arctic Circle and west to the Bering Sea shelf [*Moll-Stalcup*, 1989]. This volcanism overlaps several tectonostratigraphic terranes as well as the eastern margin of the Yukon-Koyukuk province, a vast wedge-shaped Cretaceous depression thought by some workers to be an entrapped piece of late Paleozoic and Mesozoic oceanic crust. The Yukon-Koyukuk province is composed of the Koyukuk terrane and overlying Cretaceous terrigenous sedimentary rocks. The Koyukuk terrane is predominantly Lower Cretaceous andesitic volcanic and volcaniclastic rocks. Subordinate late Paleozoic basalt, diabase, ultramafic rocks, and limestone; and Jurassic tonalite and trondhjemite also occur within the Yukon Koyukuk province [*Patton et al.*, 1989]. The province is rimmed on the north and south by narrow fault-bounded belts of ophiolitic rocks of the (composite) Angayucham-Tozitna terrane that dip beneath the Koyukuk terrane [*Patton et al.*, 1977] (Figures 1 and 2). Bordering the depression, outside the ophiolitic rocks, are Precambrian(?) and Paleozoic schists and carbonate rocks of the Brooks Range and Seward Peninsula and the Ruby, Nixon Fork, and Minchumina Terranes (Figure 1). Small ophiolite klippen of late Paleozoic to Jurassic age overlie the schists and carbonate rocks of the Brooks Range and Ruby terrane. These ophiolitic rocks have been interpreted by *Patton et al.* [1977] as allochthonous sheets that were originally continuous with the ophiolitic rocks that rim and dip beneath the Yukon-Koyukuk province. Considerable controversy centers on the relationship between the Yukon-Koyukuk province, the ophiolitic rocks, and the surrounding continental borderlands. Some workers have argued that the bordering continental crust extends

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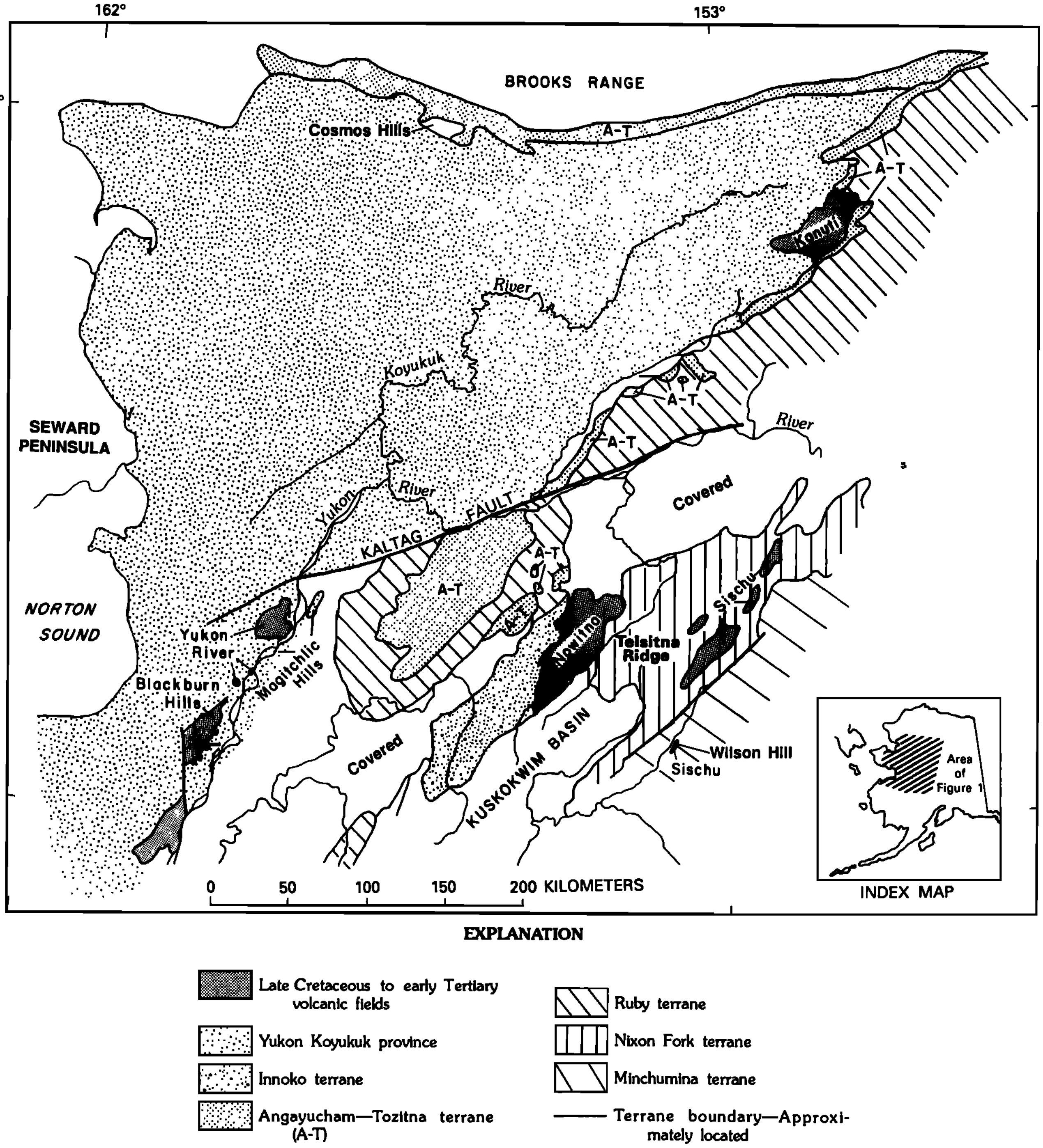


Fig. 1. Map showing the Yukon-Koyukuk province, several adjacent tectonostratigraphic terranes, and the five Late Cretaceous to early Tertiary volcanic fields studied herein. The basement rocks in the Brooks Range and Seward Peninsula and the Ruby, Nixon Fork, and Minchumina terranes consist of Precambrian(?) and Paleozoic continental crust. The Angayucham-Tozitna terrane consists of mafic and ultramafic rocks having oceanic affinities. The Innoko terrane consists of basalt, diabase, and chert. The Yukon-Koyukuk province consists mainly of a Jurassic to Cretaceous island arc assemblage overlain by mid-Cretaceous clastic rocks.

under the entire Yukon-Koyukuk province, beneath the upper Paleozoic and Mesozoic volcanic and sedimentary rocks [*Gemuts et al.*, 1983], whereas others have argued that the Yukon-Koyukuk province represents a trapped piece of late Paleozoic to Mesozoic island arc crust that collided with the continent in the Early Cretaceous time and therefore has no cratonal roots [*Patton*, 1984; *Box and Patton*, this issue]. Thus the basement of the Yukon-Koyukuk province is either oceanic (or island arc) crust or Precambrian(?) and Paleozoic continental crust buried beneath a thick blanket of andesitic rocks and clastic deposits (Figure 2).

We studied five Late Cretaceous to early Tertiary volcanic fields that overlie the Yukon-Koyukuk province and the Ruby, Nixon Fork, and Minchumina terranes in order to

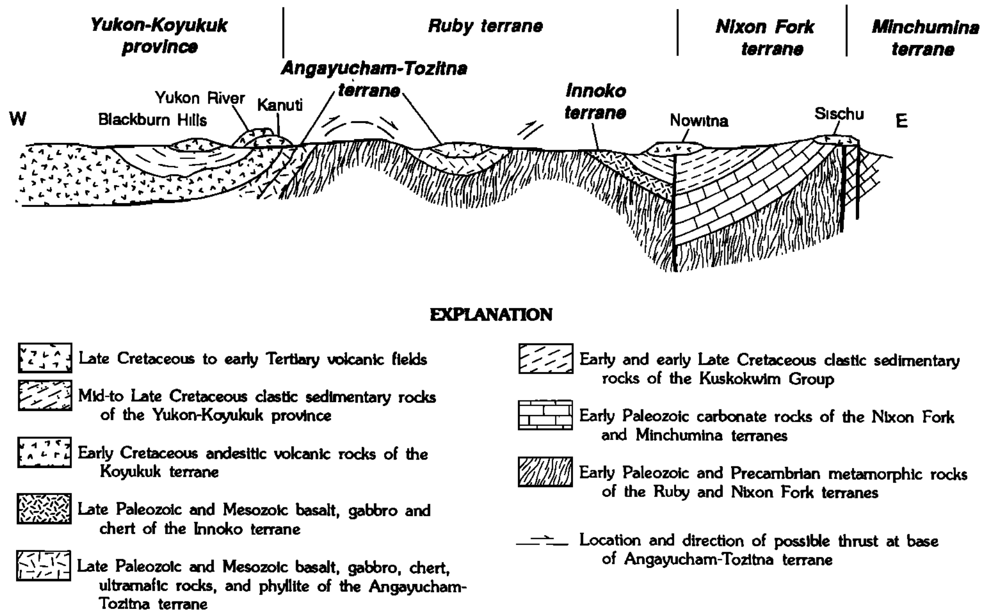


Fig. 2. Cartoon east-west cross section across the southeast margin of the Yukon-Koyukuk province and the Ruby, Nixon Fork, Innoko, and Minchumina terranes showing major rock units. The five Late Cretaceous to early Tertiary volcanic fields described in this paper are projected onto the schematic east-west cross section. From west to east the volcanic fields are the Blackburn Hills, the Yukon River, and Kanuti, which all occur along the margin of the Yukon-Koyukuk province, and the Nowitna and Sischu, which overlie Paleozoic or older schist. Geologic controversy centers on whether older continental schists of the Ruby terrane extend beneath the Yukon-Koyukuk province (marked by queries on figure) or if the boundary between the Yukon-Koyukuk province and the Ruby terrane represents a fundamental suture between upper Paleozoic and Mesozoic oceanic rocks of the Yukon-Koyukuk province and old continental crust.

chemically and isotopically characterize these previously unanalyzed rocks and to see if their composition would indicate the presence of continental crust beneath the Yukon-Koyukuk province and its southern borderlands. Three of the fields, the Blackburn Hills, Yukon River, and Kanuti, occur within the Yukon-Koyukuk province and two, the Sischu and Nowitna, overlie Precambrian and Paleozoic metamorphic rocks of the Ruby, Minchumina, and Nixon Fork terranes (Figure 1).

In this paper we compare the composition of Late Cretaceous to early Tertiary volcanic rocks erupted through the Yukon-Koyukuk province with contemporaneous rocks erupted through the older metamorphic terranes to the southeast. If the crustal section in the Yukon-Koyukuk province consists of late Paleozoic and Mesozoic oceanic or island arc crust overlain by andesitic volcanic rocks and sediments, the isotopic composition of magmas emplaced through it might be different from that of magmas emplaced through Paleozoic or older continental crust.

Crustal attributes may be reflected in magma compositions: either because mantle-derived magmas assimilate crustal material as they rise to the surface or because magmas originate in the upper or lower crust. Most of the Late Cretaceous and early Tertiary rocks comprise a wide continental magmatic arc. The rocks are highly fractionated and heat balance considerations probably require assimilation during fractionation [*Bowen*, 1928; *DePaolo*, 1981].

GEOLOGY AND GEOLOGIC SETTING OF THE FIVE VOLCANIC FIELDS

The Nowitna volcanic field consists of at least 1500 m of columnar jointed lava flows exposed in a northeast trending syncline that is fault-bounded on the southeast flank. The volcanic field has an estimated volume of 2500 km^3. The flows are chiefly andesite with minor interbedded rhyolite. Six small, highly altered, rhyolite domes overlie the flows in isolated localities throughout the field. Samples for this study were collected near the top of the stratigraphic section where a series of flows is exposed along ridges perpendicular to the strike of the syncline. Samples from the section give K/Ar whole rock ages of 63.8 ± 2.7, 66.2 ± 2.8, and 62.9 ± 2.8 Ma [*Moll et al.*, 1981; *Silberman et al.*, 1979].

The Sischu volcanic field is located east of the Nowitna field in the Sischu Mountains at the northern end of the Kuskokwim Mountains (Figure 1 and *Moll-Stalcup* [1989]). The principal volcanic rocks are at least 500 m thick and consist of a narrow, northeast trending field that appears to dip homoclinally to the southeast to its faulted margin. The main field has an estimated volume of 350 km^3. The field also includes felsic volcanic rocks exposed to the northeast along strike with the main field, a small body of rhyolite exposed along the north fork of the Kuskokwim River near Wilson Hill, and a fault-bounded block of felsic volcanic rocks in the Telsitna Ridge area (Figure 1) [*Patton et al.*, 1980]. Much of the field is covered by dense brush, except for a few high rounded knobs and the cut banks of rivers. The field consists chiefly of highly altered rhyolite and dacite breccias, flows, domes, and tuffs. One andesite dike crops out as a resistant spine in the southern part of the main volcanic field. K/Ar ages of 66.3 ± 2.0 Ma on sanidine and 69.9 ± 2.7 Ma and 71.0 ± 2.8 Ma on whole rock samples indicate a Late Cretaceous age [*Moll et al.*, 1981].

The Nowitna and Sischu volcanic fields are underlain by Precambrian and Paleozoic continental crust (Figure 2). The

Nowitna volcanic field overlies the Nixon Fork, Innoko, and Ruby terranes, and the Sischu field overlies the Nixon Fork and Minchumina terranes [*Patton et al.*, 1989]. In the vicinity of the Nowitna volcanic field, the Nixon Fork terrane consists of greenschist facies metasedimentary and metaigneous rocks overlain by Cretaceous clastic rocks [*Patton et al.*, 1980]. Discordant U-Pb ages on metavolcanic rocks in the Nixon Fork terrane, from a locality east of the Nowitna field, define two cords having upper concordia intercepts of 850 and 1265 m.y., which suggest Precambrian protoliths for the Nixon Fork terrane [*Dillon et al.*, 1985].

The Ruby terrane consists of greenschist and amphibolite-facies metasedimentary, metavolcanic, and felsic metaplutonic rocks that appear, from sparse fossil data, to have Paleozoic protoliths. Two discordant U-Pb ages from orthogneiss are insufficient to determine the age of the protolith but are compatible with the Paleozoic fossil ages [*Dillon et al.*, 1985]. *Patton et al.* [1987] report Devonian U-Pb ages of 390 ± 12 Ma on orthogneiss from the Ruby terrane north of the Kaltag fault. A U-Pb age of 2.07 Ga has been obtained on orthogneiss in the western Iditarod quadrangle (M. L. Miller, U.S. Geological Survey, personal communication, 1988). This orthogneiss may be part of the Ruby terrane that has been offset right laterally along the Kaltag fault. The Innoko terrane underlies the western part of the Nowitna field. It structurally overlies the Ruby terrane and consists of an oceanic assemblage of chert, basalt, diabase, and volcaniclastic rocks that yields Mississippian to Jurassic fossil ages [*Patton*, 1978].

In the vicinity of the Sischu field, the Nixon Fork terrane consists of greenschist facies metamorphic rocks similar to those underlying the Nowitna field, overlain by Silurian to Devonian limestone and dolomite. The Nixon Fork terrane structurally overlies the Minchumina terrane in the vicinity of the Sischu field (Figure 2). The Minchumina terrane consists of lower Paleozoic chert and phyllite underlain by quartzite, grit, and argillite and their metamorphosed equivalents of Precambrian and early Paleozoic age [*Patton et al.*, 1980]. Thus lower Paleozoic and Precambrian metamorphic rocks form the basement of both the Nixon Fork and Minchumina terranes and are therefore presumed to underlie the entire Sischu field.

The Blackburn Hills volcanic field lies within the Yukon-Koyukuk province south of the Kaltag fault, where the southern part of the province is offset right-laterally relative to the northern part (Figure 1). It is well exposed and was therefore mapped and sampled in more detail than the other fields we studied. E. J. Moll-Stalcup and J. G. Arth (manuscript in preparation, 1989) describe the field relations, chemistry, and isotopic composition of the volcanic field, which are only briefly summarized here. The volcanic rocks are exposed in a northeast trending syncline that is fault-bounded on the northwest and west flanks and conformably overlies Upper Cretaceous terrigenous sedimentary rocks on the east flank. The main volcanic field has an estimated volume of 400 km^3. A small volcanic field of approximately equal volume occurs to the south and appears to be a part of the Blackburn Hills field that has been offset left-laterally about 35 km along the Thompson Creek fault. This southern volcanic field appears to be composed entirely of east dipping andesite flows. The main volcanic field consists of a section over 1000 m thick of chiefly andesite flows that are exposed along the flanks of the syncline. The andesite flows grade up into interlayered andesite, basalt, and rhyolite. A thick section of highly altered green tuff occurs in the center of the volcanic field along the axis of the syncline, and this tuff is intruded by a granitic pluton. Hornblende from an andesite at the base of the volcanic field gives a K/Ar age of 65.2 ± 3.9 Ma; sanidine from a rhyolite dome near the top of the section gives an age of 56.0 ± 1.7 Ma; and biotite from the granitic pluton gives an age of 56.2 ± 1.7 Ma [*Patton and Moll*, 1985].

The Blackburn Hills volcanic field overlies Cretaceous sedimentary rocks in a part of the Yukon-Koyukuk province where the sedimentary basin appears to be relatively shallow (W. W. Patton, Jr., personal communication, 1988). Some of the oldest rocks in the province, including late Paleozoic basalt, diabase, and ultramafic rocks and an elongate, fault-bounded Jurassic tonalite and trondhjemite pluton, occur in the area surrounding the Blackburn Hills volcanic field. The nearest outcrops of older continental rocks are metamorphosed lower Paleozoic rocks of the Ruby terrane, located 65 km east of the Blackburn Hills [*Chapman et al.*, 1985].

The Kanuti volcanic field occurs within the northeastern part of the Yukon-Koyukuk province along its southeasternmost margin (Figure 1). The field consists of a section more than 2 km thick of chiefly dacite flows and has an estimated volume of over 1500 km^3. Most of the volcanic field is covered by dense brush except several high ridges in the eastern part of the volcanic field where most of the samples were collected. The Kanuti volcanic field was previously dated as early Tertiary in age. One K/Ar age of 59.5 ± 1.7 Ma was obtained on hornblende from a sample collected from a cutbank of the Kanuti River, and a similar age of 59.6 ± 1.8 Ma was obtained on biotite from a sample near the base of the section [*Patton and Miller*, 1973; M. A. Lanphere, written communication, 1986] (Table 1). The top of the section is dated by a biotite K/Ar age of 55.9 ± 1.7 Ma (M. A. Lanphere, written communication, 1986) (Table 1).

The eastern half of the Kanuti volcanic field overlies ophiolitic rocks and associated basalts of the Angayucham-Tozitna terrane. The western half of the volcanic field overlies Upper Cretaceous quartz-pebble conglomerates which were derived from erosion of the metamorphic borderlands of the Ruby terrane to the east. The dip of the terrane boundary between the Ruby, Angayucham-Tozitna, and Koyukuk terranes is uncertain in the vicinity of the volcanic field. Limited geophysical data (J. Cady, personal communication, 1985) suggest that the contact between the ophiolitic rocks and the Ruby terrane schists dips to the west, under the basin, which suggests that the Ruby terrane schists may extend beneath the volcanic field at depth (Figure 2).

The Yukon River volcanic rocks comprise several small isolated domes and cones and one large, poorly exposed volcanic field that crop out along the Yukon River (Figure 1) between Eagle Slide and the village of Kaltag. The most prominent volcanic bodies include a morphologically well-preserved andesite cone having a breached wall on the southeast flank, located 10 km west of the Yukon River, a large composite rhyolite dome located upriver at Eagle Slide, and a large poorly exposed volcanic field located 25–30 km farther upriver. The volcanic field, herein named the Poisen Creek volcanic field, has an estimated volume of at least 200 km^3 and may contain a caldera, as defined by arcuate creek drainages and the occurrence of several rhy-

TABLE 1. Previously Unpublished K/Ar Ages on Yukon River Area and Kanuti Volcanic Fields

Field	Material Dated	Percent K_2O	^{40}Ar rad, mol/g	^{40}Ar rad / ^{40}Ar total	Calculated Age, Ma
		Yukon River Area			
81Pa323	basalt whole rock	1.688 ± 0.004	1.200×10^{-10}	0.93	48.7 ± 1.5
81Pa319	biotite	8.085	5.977×10^{-10}	0.81	50.6 ± 1.5
	hornblende	0.6515	4.524×10^{-11}	0.53	47.6 ± 1.4
		Kanuti			
73Pa261B (near base)	biotite	8.99	7.846×10^{-10}	0.87	59.6 ± 1.8
73Pa262 (near top)	biotite	8.84	7.227×10^{-10}	0.89	55.9 ± 1.7

Ages courtesy of M. L. Lanphere; potassium measurements, L. B. Schlocker and S. T. Neil; argon measurements and age calculation, J. C. Von Essen and S. J. Kover. Constants: $\lambda\varepsilon = 0.572 \times 10^{-10}$ yr^{-1}; $\lambda\varepsilon' = 8.78 \times 10^{-13}$ yr^{-1}; $\lambda\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K/K = 1.167 \times 10^{-4}$ at. %.

olite domes (W. W. Patton, Jr., personal communication, 1983). More recently, *Doherty and Bergman* [1987] explored the Poisen Creek volcanic field and found caldera fill deposits consisting of interbedded andesitic to rhyolitic welded ash flow tuffs and andesite to dacite lava flows.

All the dated samples in the Yukon River area have Eocene K/Ar ages, and are the youngest volcanic rocks in the widespread Late Cretaceous to early Tertiary volcanic province of western Alaska [*Moll-Stalcup*, 1989]. They were erupted during a time of tectonic transition from subduction- to post-subduction-related magmatism [*Moll-Stalcup*, 1989]. A thick dacite flow exposed along the Yukon River in the Poisen Creek volcanic field gives a biotite K/Ar age of 50.6 ± 1.5 Ma and a hornblende age of 47.6 ± 1.4 Ma (M. A. Lanphere, written communication, 1983) (Table 1). An andesite flow from the southern part of the same volcanic field gives a whole rock K/Ar age of 48.7 ± 1.5 Ma (M. A. Lanphere, written communication, 1987) (Table 1). *Doherty and Bergman* [1987] also report an older age of 56 Ma from the Poison Creek field. Sanidine from the rhyolite dome at Eagle Slide gives a K/Ar age of 53.2 ± 1.6 Ma and the small cone west of the Yukon River gives a whole rock age of 53.8 ± 1.6 Ma [*Patton and Moll*, 1985]. *Harris* [1985] reports similar K/Ar ages, ranging from 49.0 to 53.7 Ma, from volcanic rocks collected along this stretch of the Yukon River.

The Yukon River volcanic rocks overlie mid- to Upper Cretaceous sedimentary rocks within the Yukon-Koyukuk province. The eastern margin of the Yukon-Koyukuk province is exposed about 15 km due east of the Yukon River volcanic rocks in the Magitchlie Hills. Rocks in the Magitchlie Hills include Lower Cretaceous(?) andesitic rocks, basaltic rocks of the Angayucham-Tozitna terrane, and marginal basin conglomerates derived from erosion of the Angayucham-Tozitna and Ruby terranes (W. W. Patton, Jr., personal communication, 1988). The Ruby terrane crops out about 10 km farther east in the Kaiyuh Mountains.

CHEMICAL AND ISOTOPIC CHARACTER OF THE COUNTRY ROCK

Although little isotopic data are available for the Paleozoic or older continental crust, Rb/Sr and Sm/Nd data on the metamorphic terranes indicate that they probably have high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$. Ten analyses of pelitic schist, metagabbros, and metasediments from the Slow Fork and Nixon Fork terranes have an average Rb/Sr of 1.5, which would correspond to an average $^{87}Sr/^{86}Sr$ of 0.7252 assuming an initial ratio of 0.703 and a mid-Paleozoic age (360 Ma). One analysis on a quartz-mica schist from the Ruby terrane has a present-day $^{87}Sr/^{86}Sr$ ratio of 0.7383 [*Blum et al.*, 1987] and a calculated ratio of about 0.735 for the early Tertiary. Cretaceous plutons intruding the Ruby terrane have high initial $^{87}Sr/^{86}Sr$ of 0.706–0.729 and initial $^{143}Nd/^{144}Nd$ of 0.5115–0.5124 [*Arth et al.*, this issue]. All of the metamorphic rocks we analyzed are light rare earth element (LREE)-enriched having La/Yb_n ratios between 1.8–3 (metagabbros) and 28 (quartz-mica schist), which would correspond to a maximum $^{143}Nd/^{144}Nd$ between 0.51241 and 0.51258 assuming a mid-Paleozoic age.

Limited $^{87}Sr/^{86}Sr$ data on the mafic Angayucham-Tozitna terrane give initial values of 0.7032 on gabbro and pyroxenite from the Kanuti ophiolite and 0.7042–0.7046 on basalt along the northern margin of the Yukon-Koyukuk (J. G. Arth et al., unpublished data, 1988). These values would be the same to very slightly higher in the early Tertiary. Most of the Koyukuk terrane consists of tholeiitic and calc-alkalic andesites, and no isotopic analyses are available for these rocks. However, S. Bergman (personal communication, 1987) reports an $(^{87}Sr/^{86}Sr)_i = 0.7076$ and measured $^{143}Nd/^{144}Nd = 0.51248$ on shoshonitic rocks dated at 118 Ma [*Patton and Moll*, 1985] that crop out near the Blackburn Hills volcanic field.

VOLCANIC FIELDS OVERLYING THE PRECAMBRIAN AND PALEOZOIC BORDERLANDS

Chemistry, Mineralogy, and Isotopic Composition

The Nowitna volcanic field consists chiefly of one- and two-pyroxene andesite having between 54 and 63 wt % SiO_2 (Table 2). (Tables, 2, 3, and 4 are major element chemistry.) Minor altered rhyolite having 72% SiO_2 occurs as domes overlying the andesite flows. Nowitna rhyolites have phenocrysts of plagioclase, sanidine, and magnetite ± biotite. The Nowitna rocks are subalkaline on a plot of total alkalis versus SiO_2, lack Fe enrichment, and cross at 60.5 wt % SiO_2 (calc-alkalic) on a Peacock diagram. The andesites are classified as medium-K calc-alkalic, orogenic andesites by the criteria of *Gill* [1981].

Most of the Nowitna samples show smooth trends on Harker diagrams for major and trace elements, which suggests that the rocks may be comagmatic (Figure 3). K, Rb, La, Ba, and Th increase and Ca, Mg, Fe, Ti, and Sr decrease

TABLE 2. Representative Major and Trace Element Data for Rocks From the Nowitna and Sischu Volcanic Fields

	Nowitna Field					Sischu Field				
	75Ch67	81ML.1	81ML.2	81ML.3	81ML.5	79Pa12	78Pa36a	78Pa56a	75Pa155	77Pa202
Latitude	64°04′57″	63°52′20″	63°14′05″	63°51′4″	63°51′10″	63°52′10″	63°57′20″	63°27′05″	63°27′00″	63°50′40″
Longitude	155°40′04″	155°14′15′	155°14′00″	155°12′50″	155°12′00″	153°12′40″	152°03′20″	153°42′20″	153°42′25″	153°13′00″
					Weight Percent					
SiO_2	53.92	56.5	60.8	59.7	62.5	60.4	72.8	76.3	75.3	70.7
Al_2O_3	17.05	16.3	15.9	16.2	15.1	17.7	14.7	12.5	12.5	15.5
Fe_2O_3	2.67	3.6	3.08	3.37	4.09	2.36	1.51	0.94	1.22	1.81
FeO	4.63	3.5	2.5	3.1	2.5	2.53	0.06	0.15	0.18	0.66
MgO	4.25	4.97	3.12	2.14	1.46	1.30	0.08	0.10	0.08	0.05
CaO	8.54	7.12	5.61	4.97	3.93	5.39	0.80	0.89	0.90	0.34
Na_2O	3.61	3.36	3.39	3.68	3.79	3.78	4.42	2.74	2.71	1.32
K_20	1.62	1.85	2.43	2.86	3.22	2.62	5.44	5.24	5.42	6.52
TiO_2	1.18	1.11	0.94	1.38	1.26	0.87	0.13	0.14	0.18	0.31
P_2O_5	0.36	0.31	0.30	0.42	0.40	0.20	0.03	0.10	0.02	0.12
MnO	0.13	0.10	0.06	0.09	0.10	0.06	<0.01	0.02	<0.01	0.01
CO_2	1.69	0.02	0.08	0.01	0.01	0.87	0.06	0.05	0.06	0.05
H_2O^+	0.57	0.38	0.71	0.52	0.59	1.25	0.31	0.43	0.61	2.10
H_2O^-	0.85	0.56	0.71	0.83	0.54	0.64	0.47	0.43	0.37	0.65
Total	101.07	99.68	99.63	99.27	99.49	99.97	100.85	100.03	99.54	100.14
					Parts per Million					
Rb	50	48	75	90	89	104	742*	188*	199	245
Cs	0.65	0.6	0.9	1.5	1.9	2.41	46.7	5.67	0.4	6.65
Sr	525	498	479	475	337	408	9.5*	51.4*	55	156
Ba	846	920	1290	1350	1510	789	5	512	537	1295
La	30	33	38	44	48	32.3	262	83.5	44	59
Ce	54.5	60	69	81	91	63	305	166	71	100.5
Nd	29.5	26	32	36	45	30	160	62.5	28	38.5
Sm	5.75	5.3	5.8	7.4	9.0	5.88	27.2	10	4.2	7.35
Eu	1.37	1.36	1.32	1.69	1.84	1.3	0.56	0.715	0.89	1.16
Gd	3.9	5	5.5	7.3	7.6	5.97	31.6	8.0	4	3.45
Tb	n.a.	0.7	1.71	1.02	1.22	0.747	3.86	0.811	0.36	0.48
Tm	0.51	0.34	0.3	0.43	0.47	<0.5	1.46	<0.5	<0.09	<0.30
Yb	2.45	2.3	2.2	0.31	4.3	2.69	11	2.19	0.9	0.65
Lu	0.36	0.33	0.33	0.44	0.62	0.404	1.37	0.293	0.13	0.085
Y	28	23	27	33	40	24	112	27	26	n.d.
Zr	199	177	215	253	290	176	387	226	242	418
Hf	3.9	4.1	4.9	5.8	7.1	4.7	14.8	7.01	4.3	7.75
Nb	12	9	15	18	16	16	111	20	24	31
Ta	0.665	0.79	0.84	1.13	1.28	1.42	8.55	1.51	1.26	2.26
Th	6.55	8.2	10.1	11.3	13.1	13.1	125	28.3	27.6	18.5
U	2.35	2.3	3.0	3.5	3.9	5.54	26.2	6.49	6.67	11.1
Sc	19.5	19.7	15.2	14.5	16.6	8.77	0.79	1.14	2.13	1.8
Cr	50.7	77.3	36.1	9.5	2.0	6.61	<0.5	0.713	1.8	3.1
Co	25.8	23.5	14.2	12.6	10.5	12	0.3	0.441	1.2	2.75
Zn	92.5	79	80	94	106	n.d.	106	n.d.	20	57
Sb	<0.6	<0.5	0.2	0.3	0.5	0.27	n.d.	1.52	n.d.	0.5
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	1.9	17.0	2.4	3.0	3.8
W	n.d.	n.d.	n.d.	n.d.	n.d.	1.6	22.0	2.8	360	3.0
F	n.d.	n.d.	n.d.	n.d.	n.d.	400	3000	200	200	800
Be	n.d.	n.d.	n.d.	n.d.	n.d.	2.1	11.0	2.0	2.5	3.0

n.d., not determined.

with increasing SiO_2 (Figure 3). Two of the Nowitna samples, 81ML3 and 81ML5, have higher TiO_2, P_2O_5, FeO*, and K_2O and lower MgO, and CaO than the other samples. The andesites are LREE-enriched, having La of 90–115 and Lu of 11–13 × chondrites (Figure 4). The Nowitna rhyolites have similar shaped patterns to the andesites, but slightly higher chondrite-normalized REE values (La-140, Lu-15) and a moderate negative Eu anomaly (Figure 4). The rocks are chemically similar to arc lavas, being enriched in K, Ba, Rb, Th, and Sr and depleted in Nb, Ta, and Ti relative to the REE (Figure 5) [*Arculus and Powell*, 1986]. However, the suite has high absolute abundances of all incompatible elements, such that Nb and Ta contents are high relative to most arcs, although still depleted relative to the alkali and rare earth elements.

Three of the analyzed andesites from the Nowitna field, ranging in SiO_2 from 54 to 59 wt %, have very similar initial isotopic ratios. Average initial $^{87}Sr/^{86}Sr$ is 0.70444 and average initial $^{143}Nd/^{144}Nd$ is 0.51257 (Table 5). Because the mafic to ultramafic source areas for basaltic to andesitic rocks show little isotopic change since the Paleocene, the initial ratios reported here can be compared to the fields measured for Recent volcanic rocks. Three of the Nowitna samples plot within the "mantle array," defined by typical compositions of Recent MORB and oceanic island volcanic rocks of the northern hemisphere, and near "bulk earth"

TABLE 3. Representative Major and Trace-Element Analyses for Rocks From the Kanuti Volcanic Field

	Sample							
	81ML314	81ML303	81ML300	81ML311	81ML319a	81ML307	81Pa400a	81Pa400a
Latitude	66°27′00″	66°23′00″	66°23′00″	66°27′00″	66°24′40″	66°24′05″	66°25′50″	66°26′20″
Longitude	150°52′00″	150°55′10″	150°55′00″	150°53′10″	150°53′00″	150°53′40″	150°58′10″	150°58′20″
				Weight Percent				
SiO_2	64.0	65.7	64.0	65.3	65.8	67.8	68.8	71.5
Al_2O_3	16.1	15.6	16.0	15.3	15.8	14.8	15.0	13.5
Fe_2O_3	3.01	2.98	3.36	3.1	2.67	2.85	2.89	2.87
FeO	1.2	0.84	0.88	0.92	0.84	0.52	0.04	0.12
MgO	2.09	1.56	1.98	1.51	1.45	1.14	0.64	0.52
CaO	4.55	4.39	4.72	4.08	3.91	3.59	2.82	2.94
Na_2O	3.62	3.45	3.46	3.74	3.48	3.51	3.82	3.18
K_20	2.55	2.65	2.48	3.3	3.06	2.9	3.53	3.23
TiO_2	0.58	0.49	0.56	0.58	0.48	0.44	0.5	0.41
P_2O_5	0.22	0.19	0.27	0.39	0.19	0.19	0.14	0.16
MnO	0.01	0.02	0.03	0.07	0.04	0.04	0.04	0.03
CO_2	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
H2O+	0.83	0.8	0.81	0.59	1.6	0.66	0.52	0.33
H2O−	0.87	0.87	0.8	0.51	0.41	0.48	0.68	0.39
Total	99.66	99.55	99.37	99.40	99.74	98.94	99.44	99.20
				Parts per Million				
Rb	84	85	78	102	85	118	120	104
Cs	2	2	3.1	6	2.7	2.7	5.9	3
Sr	610	543	691	875	599	632	453	439
Ba	1650	1640	1580	1920	1740	1710	2053	2010
La	61	54	59	71	70	66	61	56
Ce	95	87	95	122	109	105	96	97
Nd	38	27	33	45	37	36	31	28
Sm	7	5	5.3	6.9	5	5.1	5	4.7
Eu	1.28	1.13	1.28	1.44	1.17	1.16	1.12	0.99
Gd	4.7	3.7	5.5	5.9	3.6	4.4	5.3	<3.0
Tb	0.52	0.39	0.42	0.5	0.42	0.38	0.45	0.4
Tm	0.11	0.14	0.17	0.24	0.19	0.19	n.a.	0.27
Yb	1.5	1.2	1.2	1.6	n.a.	1.1	1.5	1.3
Lu	0.2	0.16	0.17	0.23	0.15	0.16	0.22	0.2
Y	21	16	16	16	16	15	18	17
Zr	198	179	184	205	209	219	222	156
Hf	4.5	4.2	4.1	4.8	4.6	4.4	5.1	44.2
Nb	11	9	10	13	12	13	13	13
Ta	0.84	0.77	0.77	1.05	0.89	0.86	1.12	0.87
Th	15	15.7	13.6	14.4	16.6	16.2	19.5	18.4
U	4.7	3.9	3.3	4.3	4	3.8	5.8	4.8
Sc	9.94	8.65	9.38	8.05	7.08	6.48	5.6	6.57
Cr	52.3	47.9	56	27.6	29.7	30.1	9.9	28.9
Co	11.6	10.9	11.7	9.5	8.8	7.9	4.6	6.3
Zn	66	55	66	65	58	46	53	34
Sb	0.2	0.3	0.3	0.4	0.3	0.2	0.5	0.4

n.a., not accurately determined.

compositions for 65 Ma (Figure 6). A fourth sample of high-silica andesite has significantly higher initial $^{87}Sr/^{86}Sr$ (0.7051) but identical initial $^{143}Nd/^{144}Nd$ and plots off the "mantle array" in the high $^{87}Sr/^{86}Sr$ field (Figure 6).

The Sischu volcanic rocks are chiefly rhyolite and dacite, with minor andesite dikes. Mafic minerals in the Sischu samples are often altered beyond recognition, but typical primary mineral assemblages include quartz + oligoclase + sanidine + biotite or fayalite in rhyolites, plagioclase (andesine to oligoclase) + sanidine + biotite in dacites, and plagioclase + hornblende + magnetite + biotite (secondary?) in andesites. Their mineralogy is like the high-K dacite and rhyolite series of *Ewart* [1979] which occurs in New Zealand and in the western United States.

The Sischu rocks are more altered and K_2O and Na_2O values are less reliable than those of the Nowitna rocks, but K_2O/Na_2O are 1–2 in the least altered felsic samples and are about 0.7 in the andesite sample. The Sischu volcanic rocks are characterized by low TiO_2, high K_2O/Na_2O, and high Al_2O_3 and are classified as shoshonitic to high-K calc-alkalic. In this paper we use the term shoshonitic to describe rocks that are enriched in large ion lithophile (LIL) and depleted in high-field strength elements like arc rocks but higher in K and most incompatible elements than high-K calc-alkalic rocks [*Morrison*, 1980]. The rocks plot along the alkalic-subalkalic boundary on a total alkalis versus SiO_2 diagram. K_2O contents of the least altered rocks plot in the high-K field, defined by extending the lines of *Gill* [1981] to higher silica contents.

The Sischu suite shows considerable scatter on major and trace element Harker diagrams. All the rocks are highly differentiated: the lowest volatile-free SiO_2 content is 62 wt

TABLE 4. Representative Major and Trace Element Analyses for the Yukon River Area

	Eagle Slide			Poisen Creek Area				
	1	2	3	4	5	6	7	8
Sample	81Pa332b	81Pa334	81Pa330	81Pa327	81Pa321	81Pa319	81Pa326	81Pa323
Latitude	63°46′35″	63°47′25″	63°48′15″	63°57′30″	64°01′20″	64°02′50″	64°00′02″	63°48′15″
Longitude	159°15′20″	159°14′00″	159°13′00″	158°57′00″	158°46′30″	158°45′05″	158°52′00″	158°48′20″
				Weight Percent				
SiO2	48.7	57.3	75.3	49.2	55.7	66.3	48.0	60.6
Al_2O_3	18.4	16.0	13.1	15.4	15.7	14.3	16.7	16.7
Fe_2O_3	4.23	4.19	0.6	3.53	4.5	2.74	7.28	3.09
FeO	6.1	3.0	0.08	7.0	3.8	0.72	3.8	2.8
MgO	4.24	3.45	0.15	4.24	3.26	1.27	4.47	2.74
CaO	9.31	6.74	0.41	8.49	6.86	2.77	10.8	6.22
Na_2O	3.77	3.75	3.87	3.52	3.57	2.88	3.22	3.60
K_2O	0.81	1.89	4.58	1.31	2.01	3.37	0.71	1.65
TiO_2	2.17	1.43	0.16	2.04	1.37	0.57	1.98	0.85
P_2O_5	0.66	0.39	>.05	0.72	0.46	0.18	0.49	0.28
MnO	0.19	0.11	>.02	0.19	0.17	0.08	0.15	0.10
CO_2	0.02	0.02	0.02	3.20	0.08	0.02	0.01	0.01
H_2O+	0.83	0.83	0.50	0.61	0.26	1.80	1.00	0.50
H_2O-	0.5	0.94	0.43	0.4	1.1	2.0	0.92	0.92
Total	99.93	100.04	99.20	99.85	98.94	99.26	99.53	100.06
				Parts per Million				
Rb	17	50	128	35	61	114	17	36
Cs	0.5	2	1.8	1.3	3	3.6	0	0.4
Sr	603	475	32	834	678	405	616	454
Ba	543	990	800	910	841	1230	464	1040
La	30	32	68	35	35	41	24	40
Ce	62	60	118	70	66	73	50	68
Nd	37	30	47	39	30	30	29	29
Sm	7.9	6.1	7.9	7.7	6.2	5.5	6.2	5.4
Eu	2.23	1.65	0.38	2	1.59	1.2	1.83	1.35
Gd	7.5	5.7	6.1	6.1	5.5	4.5	5.5	4.1
Tb	1.08	0.86	0.98	0.88	0.74	0.69	0.88	0.64
Tm	0.5	0.41	0.44	0.35	0.4	0.29	0	0.34
Yb	3.9	3.2	4.1	3.1	2.4	2.8	2.9	2.4
Lu	0.56	0.48	0.52	0.45	0.35	0.43	0.43	0.38
Y	32	30	37	28	23	31	27	24
Zr	209	191	207	186	166	256	154	204
Hf	4.6	4.6	6	4	3.7	5.9	3.3	4.6
Nb	14	16	30	16	17	17	15	12
Ta	0.91	1.12	2.05	1.15	1.26	1.55	0.78	0.95
Th	1.8	5.9	18.9	3.5	7.4	13.4	1.5	5.6
U	0.5	1.7	5.2	1.1	2.2	3	0.3	1.5
Sc	24.5	23.9	2.65	24.9	17.8	7.35	33.8	14.6
Cr	34.4	43.5	4.6	31.1	30.7	6.2	106	35.9
Co	28.4	25.6	0.3	31.9	28.4	5.8	39	16.4
Zn	95	99	27	96	73	53	103	71
Zb	<0.5	0.4	0.6	0	0.3	0.2	0	<0.5

Analyses: 1, basalt at Eagle Slide on the Yukon River; 2, latite at Eagle Slide on the Yukon River; 3, rhyolite from Eagle Slide, K-Ar age is 53.2 Ma; 4, basalt from small cone south of Poisen Creek, between Stink Creek and Steamboat Slough; 5, andesite from the southeast part of Poisen Creek volcanic field; 6, dacite from eastern part of Poisen Creek volcanic field, K-Ar ages on this rock yield 50.6 (biotite) and 47.6 Ma (hornblende); 7, basalt from southeast part of Poisen Creek field; 8, andesite from southeast part of Poisen Creek volcanic field, whole rock K-Ar age on this rock is 48.7 Ma.

%, and most of the rocks have more than 70 wt % SiO_2. With the exception of two highly evolved rhyolites, the Sischu suite appears to plot along the trends defined by the Nowitna data on Harker diagrams for most major and trace elements (Figure 3). An exception is Ba, which is lower in the Sischu suite and Na_2O, which shows considerable scatter in the Sischu suite. REE patterns from the Sischu volcanic rocks show considerable variation (Figure 4). The REE pattern of an andesite dike from the Sischu field is almost identical in shape and abundance to that of Nowitna andesites (Figure 4), but REE patterns for felsic rocks from the Sischu field are quite different from Nowitna rhyolites. The felsic rocks from the Sischu field show two types of REE patterns: most of the samples have steep LREE-enriched patterns, very low HREE contents, and moderate negative Eu anomalies; three samples have high to very high HREE contents and large Eu anomalies (Figure 4*c*). Although we consider SiO_2 contents in these highly altered rocks to be unreliable, the three samples having extremely high HREE and large Eu anomalies are probably high-silica rhyolites. Two of the three have SiO_2 greater than 76 wt %, and the third sample (78Pa36) has extremely high REE as well as high Be (11 ppm), Sn (17 ppm), W (22 ppm), Rb (780 ppm), and Th (127 ppm) and low Sr (9 ppm). If the andesites, rhyolite, and high-silica rhyo-

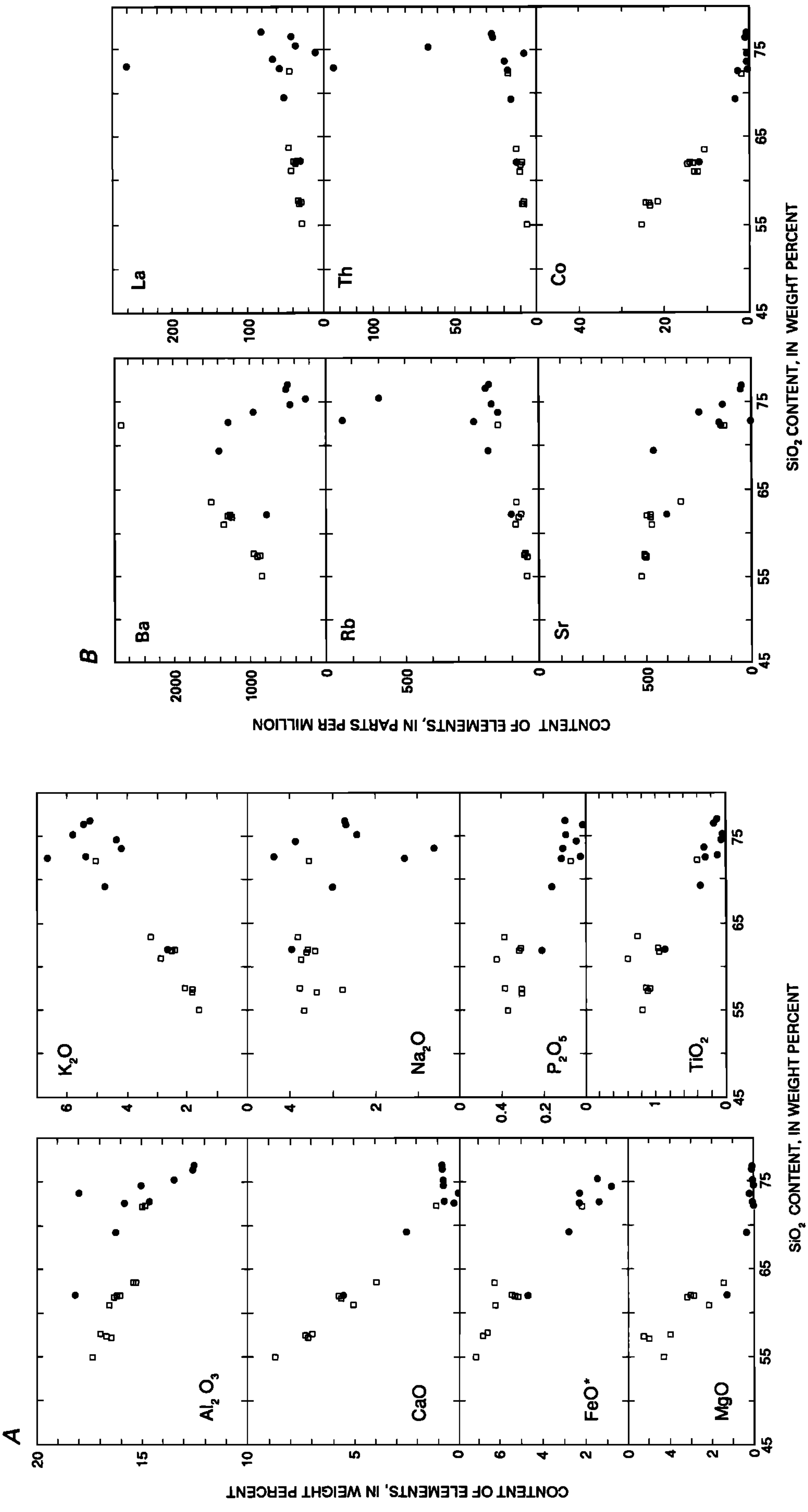


Fig. 3. Variation of (*a*) major and (*b*) trace elements with SiO_2 for the Nowitna (squares) and Sischu (solid circles) volcanic fields. The Sischu field shows greater scatter on the diagrams, largely due to greater postdepositional alteration. One high-silica rhyolite (78Pa36a) in the Sischu field has extremely high Th and La contents.

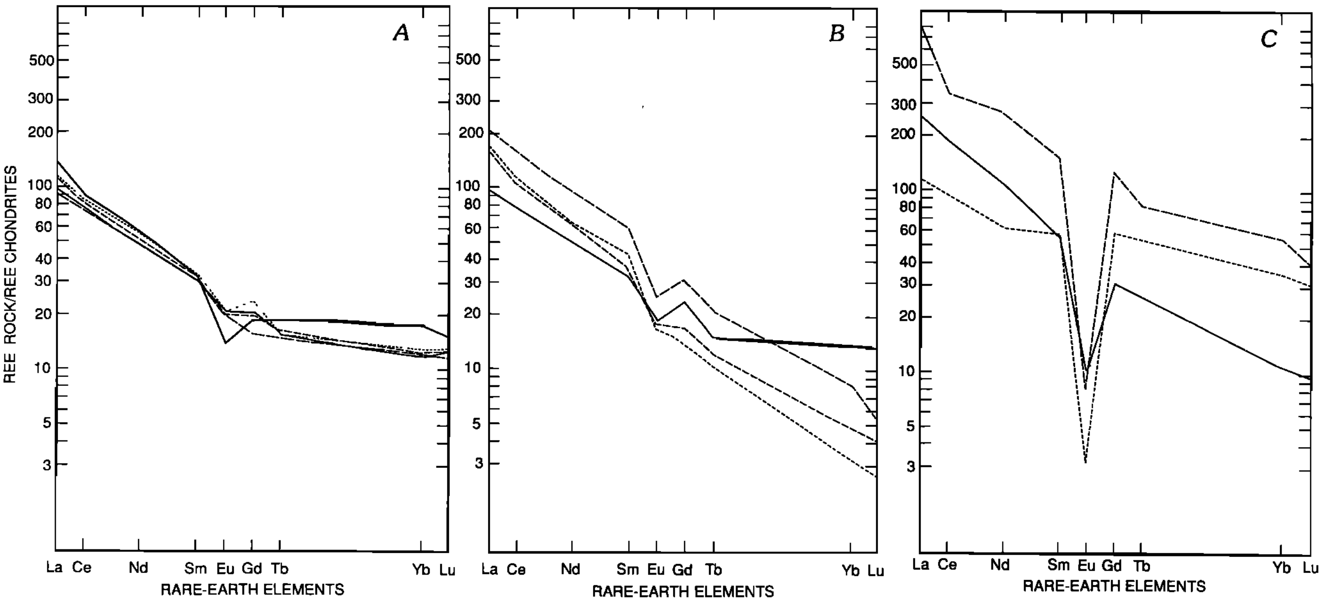


Fig. 4. Chondrite-normalized REE plots for the volcanic fields that overlie the continental borderlands surrounding the Yukon-Koyukuk province. (*a*) Nowitna andesites (dashed) and rhyolite (solid). The rhyolite has similar REE patterns but slightly higher REE, and larger Eu negative anomaly than the andesites. (*b*) Sischu andesite sample (solid) and three rhyolites (dashed). (*c*) Sischu high-silica rhyolites.

lites are related, the overall trends inferred from Th and Ti data are that the LREE increase slightly and the HREE decrease from andesite to rhyolite and that the HREE increase and Eu decreases from rhyolite to high-silica rhyolite.

Isotopic analyses were made on three of the Sischu samples, two rhyolites and one andesite. All three give values initial $^{87}Sr/^{86}Sr$ of 0.7075–0.7079 and initial $^{143}Nd/^{144}Nd$ of 0.51244–0.51247. These are indistinguishable within the calculated uncertainties and considerably higher in initial $^{87}Sr/^{86}Sr$ than the Nowitna rocks (Table 5).

Origin and Evolution of the Nowitna and Sischu Magmas

Most of the Nowitna volcanic rocks are medium-K arc andesites, and even the most mafic samples do not have the composition of unfractionated mantle-derived melts [e.g., *Mysen*, 1982]. The composition of potential basaltic parent magmas that might have fractionated to andesite is unknown, as no rocks having SiO_2 of less than 53 wt % were erupted in the region known to be underlain by Paleozoic and older metamorphic rocks. A comparison of selected trace element ratios for the Nowitna andesites with ratios for mantle-derived basalts from various tectonic environments and potential crustal contaminants indicate that most of the ratios can be interpreted as mixtures between calc-alkalic island arc basalt (IAB) and Paleozoic or older continental crust, represented by the composition of average schists (Table 6). We further note that calc-alkalic IAB has K/Rb, La/Yb, Hf/Th, and Y/Zr ratios similar to primitive basalts from the St. Michaels volcanic field, which formed in an ocean island basalt (OIB)-type mantle source [*Moll-Stalcup*, 1989]. The Nowitna andesites have Rb/Zr, La/Nb, and Zr/Nb ratios within the range for Aleutian andesites, but Ba/La and Ba/Th that are lower than either IAB or Aleutian andesites, perhaps indicating contamination by the metamorphic terrane. The isotopic composition of potential parent magmas may be similar to the andesites we analyzed, or if the Nowitna andesites are contaminated by isotopically more evolved material, the parent magmas might be lower in $^{87}Sr/^{86}Sr$ and higher in $^{143}Nd/^{144}Nd$.

The isotopic composition of the andesites does not clearly define their source because most of the initial ratios plot near "bulk earth" compositions on $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ diagrams in a field where rocks from a variety of tectonic environments (island arcs, oceanic islands) and sources (continental crust, continental, and oceanic mantle) overlap (Figure 6). Three of the Nowitna andesites have the same isotopic composition within uncertainty; one has slightly more radiogenic initial $^{87}Sr/^{86}Sr$ at the same initial $^{143}Nd/^{144}Nd$, higher SiO_2 and Nd contents, and lower Sr contents. These variations, from the most mafic Nowitna andesite to the most felsic andesite, may indicate assimilation of high-$^{87}Sr/^{86}Sr$ country rock during fractionation of a plagioclase-dominated ($D_{Sr} >>> D_{Nd}$) mineral assemblage. Phenocryst proportions in the samples indicate that the bulk distribution coefficients for Sr (D_{Sr}) are between 0.90 and 1.80 and D_{Nd} is between 0.01 and 0.24 using distribution coefficients (K_d) for andesites given by *Gill* [1981].

The most likely contaminant is Paleozoic and older continental crust of the Ruby and Nixon Fork terranes, which are thought to extend under the volcanic field beneath the Innoko terrane (Figure 2). The Innoko terrane may also be a possible contaminant if oceanic basalts in the terrane have been hydrothermally altered by interaction with seawater and have elevated $^{87}Sr/^{86}Sr$ ratios (0.7051–0.7080). Although sparse data on the oceanic terranes do not indicate the presence of seawater-hydrothermally altered rocks with elevated $^{87}Sr/^{86}Sr$, we modeled the data to see if we could eliminate this possibility. Major element fractionation-assimilation models were successfully calculated [*Geist et al.*, 1985] using continental crust as a contaminant (Table 7)

TABLE 5. Sr and Nd Isotope Data for Four Latest Cretaceous and Early Tertiary Volcanic Fields in West Central Alaska

Sample	Rb,[a] ppm	Sr,[a] ppm	$^{87}Sr/^{86}Sr$[b] (Measured)	Mass Spectrometer Precision[c]	Age, Ma	SIR[d]	Uncertainty in SIR[e]	Sm,[f] ppm	Nd,[f] ppm	$^{143}Nd/^{144}Nd$ (Measured)[g]	NIR[h]
					Nowitna Field						
81ML1	48	498	0.70472	0.00013	65	0.70447	0.00015	5.3	26.0	0.51262	0.51257
81ML2	75	479	0.70476	0.00007	65	0.70434	0.00016	5.3	32.0	0.51260	0.51256
81ML3	90	475	0.70500	0.00008	65	0.70450	0.00016	7.4	36.0	0.51262	0.51257
81ML5	89	337	0.70579	0.00011	65	0.70509	0.00017	9.0	45.0	0.51263	0.51257
					Sischu Field						
79Pa12	104	408	0.70816[i]	0.00005[i]	66.3	0.70747	0.00016	5.88	30.0	0.51249	0.51244
			0.70813	0.00006							
79Pa56	188[j]	51.4[j]	0.71798	0.00006	66.3	0.70791	0.00037	10.0	62.5	0.51251	0.51246
75Pa155	193.5[j]	50.8[j]	0.71829	0.00006	66.3	0.70791	0.00038	4.2	28.0	0.51251	0.51247
					Kanuti Field						
81ML314	84	610	0.70466	0.00008	56.0	0.70434	0.00015	7.0	38.0	0.51271	0.51267
81ML303	85	543	0.70513	0.00006	56.0	0.70477	0.00016	5.0	27.0	0.51270	0.51266
81ML300	78	691	0.70500	0.00009	56.0	0.70474	0.00015	5.3	33.0	0.51265	0.51262
81ML311	102	875	0.70473	0.00009	56.0	0.70446	0.00015	6.9	45.0	0.51258	0.51255
81ML319a					56.0			5.0	37.0	0.51261	0.51258
81ML307	118	632	0.70474	0.00013	56.0	0.70431	0.00015	5.0	36.0	0.51268	0.51265
81Pa400a	120	453	0.70525	0.00006	56.0	0.70464	0.00016	5.0	31.0	0.51268	0.51248
81Pa400b					56.0			4.7	28.0	0.51256	0.51252
					Yukon River Field						
81Pa332b	17	603	0.70380	0.00005	53.6	0.70374	0.00015	7.9	37.0	0.51273	0.51268
81Pa319	79	458	0.70546	0.00008	50.0	0.70511	0.00016	5.5	30.0	0.51270	0.51266
81Pa330	124.4[j]	28.7[j]	0.71450	0.00012	53.2	0.70502	0.00035	7.9	47.0	0.51276	0.51272
81Pa323	36	454	0.70423	0.00005	48.7	0.70407	0.00015	5.4	29.0	0.51284	0.51280
81Pa321	61	678	0.70481	0.00007	50.0	0.70463	0.00015	6.2	30.0	0.51274	0.51269

[a] Rb and Sr analyses by X ray fluorescence spectroscopy. Precision is ±5%.
[b] Sr isotopic ratios normalized to $^{86}Sr/^{88}Sr$ = 0.11940. NBC SRM987 gave a value of 0.71020.
[c] Precision of mass spectrometry on an individual sample at the 67% confidence level.
[d] SIR, initial $^{87}Sr/^{86}Sr$ ratio.
[e] Uncertainly in initial $^{87}Sr/^{86}Sr$ ratio is propagated to include uncertainties in elemental concentration measurements, isotopic ratio measurement, and reported age and is given at the 95% confidence level.
[f] Sm and Nd analyses by instrumental neutron activation. Precision is ±5%.
[g] Nd isotopic ratios noramlized to $^{146}Nd/^{144}Nd$ = 0.72190. Precision is ±0.00002. USGS rock standard BCR-1 gave a value of 0.51263.
[h] NIR, initial $^{143}Nd/^{144}Nd$. Uncertainty in initial $^{143}Nd/^{144}Nd$ is less than 0.00003 for all samples and is propagated to include uncertainties in Nd and Sm content, mass spectrometer analyses, and age assignment.
[i] Acid treated (see text).
[j] Analyzed by isotope-dilution mass spectrometry. Precision is ±0.5% for the Rb analyses and ±1% for the Sr analyses.

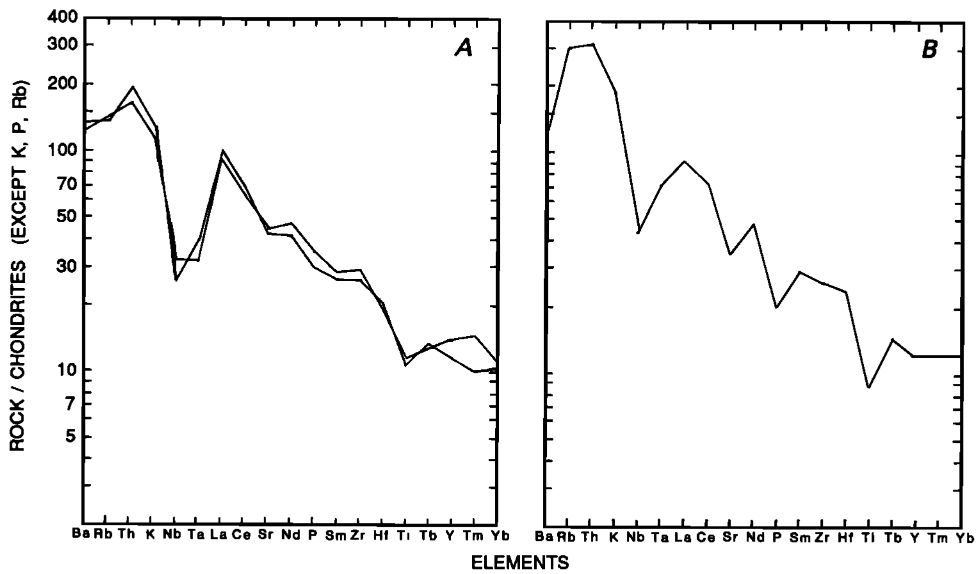


Fig. 5. Spidergrams for andesites from the Nowitna and Sischu volcanic fields. (*a*) Nowitna andesites have enriched alkalis and depleted Nb and Ta relative to La. (*b*) The Sischu andesite sample, sample 79Pa12, has a smaller Nb-Ta anomaly and more alkali enrichment. All data are normalized to values for chondrites except Rb, K, and P, which are normalized to "primitive terrestrial mantle" [*Thompson*, 1982].

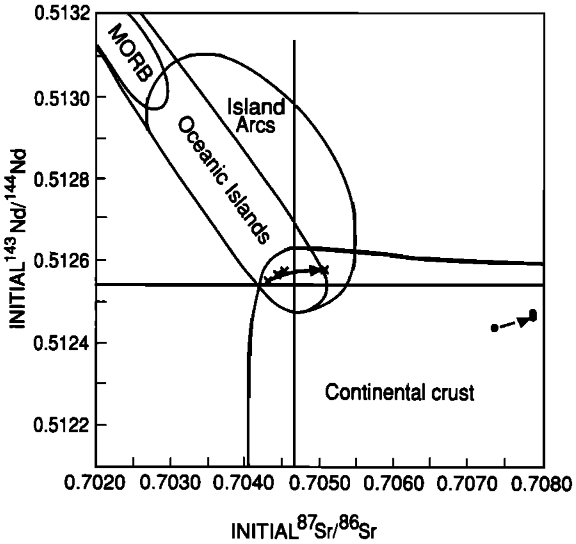


Fig. 6. Plots of initial $^{143}Nd/^{144}Nd$ versus initial $^{87}Sr/^{86}Sr$ for the Nowitna (crosses) and Sischu (solid circles) volcanic fields. Also shown are the fields for MORB, island arcs, ocean islands, and continental crust drawn to include 80% of all samples [*Zartman*, 1984]. Sischu volcanic rocks have high initial $^{87}Sr/^{86}Sr$ and low initial $^{143}Nd/^{144}Nd$ and plot in the field for continental crust. Nowitna samples plot near "bulk earth" composition at 65 Ma in an area where data from many different sources and environments overlap (including oceanic islands, island arcs, and young continental lithosphere). Bulk earth at 65 Ma ($^{87}Sr/^{86}Sr$ = 0.70467; $^{143}Nd/^{144}Nd$ = 0.51255) calculated using values found by *Allegre et al.* [1983]. Data from the Nowitna fields show a small increase in initial $^{87}Sr/^{86}Sr$ at fairly constant initial $^{143}Nd/^{144}Nd$ with increasing SiO_2. These trends may be indicative of fractionation-assimilation if the fractionating mineral assemblage contains considerable plagioclase.

but were unsuccessful using altered oceanic crust (Angayucham-Tozitna terrane), probably because the oceanic crust contains high concentrations of Ca, Mg, and Fe, whereas the Nowitna andesites and continental crust do not. Trace element modeling of assimilation-fractionation [*DePaolo*, 1981] using the continental contaminant gives reasonable Ba, Ce, Sc, and Co contents but Rb and Zr contents that are 30% too high (Table 8). However, the trace element models are poorly constrained because the models are controlled mainly by the choice of K_d and we lack data on measured K_d for these rocks. Our calculations use the major element solutions to constrain the degree of fractionation and contamination and the mineralogy of the fractionating assemblage, but allow the K_d to vary within the range of values, for example, given by *Gill* [1981].

We modeled the Nowitna isotopic data and the Sr and Nd elemental data to see if the isotopic data would further distinguish between possible oceanic and continental assimilants. The models (Figure 7) show a number of solutions that produce large shifts in $^{87}Sr/^{86}Sr$ with very little change in $^{143}Nd/^{144}Nd$, chiefly because $^{87}Sr/^{86}Sr$ change rapidly relative to $^{143}Nd/^{144}Nd$ when fractionation is dominated by feldspar ($D_{Sr} > 1$; $D_{Nd} <<< 1$) and assimilation rates are low to moderate (r less than 0.4). Thus the isotopic modeling does not clearly distinguish between sources having small to moderate differences in $^{143}Nd/^{144}Nd$ and therefore a variety of contaminants including seawater-hydrothermally altered basalt ($^{87}Sr/^{86}Sr$ = 0.708, $^{143}Nd/^{144}Nd$ = 0.5130) and Paleozoic continental crust ($^{87}Sr/^{86}Sr$ = 0.7080–0.720, $^{143}Nd/^{144}Nd$ = 0.5124–0.5118) can produce higher $^{87}Sr/^{86}Sr$ values at near constant $^{143}Nd/^{144}Nd$ (Figure 7). The best fit to the models is for contaminants 1, 2, and 6 which indicates that the Nowitna magmas were probably contaminated by isotopically moderate material having $^{87}Sr/^{86}Sr$ = 0.708–0.720 and $^{143}Nd/^{144}Nd$ = 0.5124 which would favor Paleozoic continental crust over Precambrian continental crust or oceanic crust (Figure 7). Oceanic crust is considered the least likely contaminant. The major element data do not indicate contamination by oceanic crust, and we are uncertain if seawater-hydrothermally altered oceanic rocks having $^{87}Sr/^{86}Sr$ greater than 0.7042 occur in the area.

Large volcanic fields of dacite and rhyolite, like the Sischu field, are generally thought to form by partial melting of the crust or fractionation of more mafic parent magmas. The

TABLE 6. Comparison of Trace Element Ratios Between the Nowitna Andesites, Calc-Alkalic Island Arc Basalt, Aleutian Andesites, Ocean Island Basalt, MORB, and Potential Contaminants

	MORB[a]	OIB[a]	St. Michaels[b]	Nowitna	IAB[c]	Aleutian Andesite[d]	Average Tozitna	Metamorphic Terrane Average	Metamorphic Terrane Range
SiO_2	<50	<50	48.7	55–62	54–58	53–63	50	69	49–89
K/Rb	1100	400	410	291	475	250–375	361.7	229.6	197–268
La/Yb_n	1.0	>10	7.1	8.8	7	4.0–8.5	3.2	8.8	1.8–16.8
Hf/Th	12.0	<3	1.9	0.5	1.8	0.6–1.9	2.2	0.4	0.38–0.50
Y/Zr	0.4	0.15	0.2	0.1	0.25	n.d.	0.2	n.d.	n.d.
Rb/Zr	0.01	0.1	0.1	0.3	0.2	0.2–0.4	0.1	0.3	0.12–0.46
Ba/La	4	12	11	31	40	36–56	20	21	9.8–33
Sr/Nd	18	23	19	16	48	33–50	12	5	1.7–9.3
Ba/Th	60.0	80–130	214	120	325	130–193	163	40	13.1–71.5
La/Nb	1.0	0.7	0.8	2.8	1 -2	1.2–3.4	1.1	2.2	1.5–3.0
Zr/Nb	>30.0	0.15	7.0	15.8	42	9.0–34	11.4	18.9	11.7–22.1

According to *Gill* [1984], K/Rb, La/Yb, Hf/Th, and Y/Zr ratios distinguish MORB and OIB; Rb/Zr, Ba/La, Sr/Nd, Ba/Th, La/Nb, and Zr/Nb ratios distinguish island arc basalt from either MORB or OIB. OIB, ocean island basalt; IAB, island arc basalt; n.d., not determined.
[a]Values for MORB and OIB from *Gill* [1984].
[b]St. Michael sample is a primitive tholeiite from the late Cenozoic St. Michael volcanic field located 50 km west of the Blackburn Hills volcanic field.
[c]Data for IAB from calc-alkalic andesite from Viti Levu [*Gill*, 1984].
[d]Aleutian andesite data are for Buldir and Moffett volcanoes from *Kay and Kay* [1989].

TABLE 7. Selected Fractionation-Assimilation Models for Nowitna Andesites

	Model 1: Low-Silica Andesite to High-Silica Andesite						
	Parent 75Ch67	Daughter 81ML5	Contaminant[a]	Calculated Daughter	Residuals	Solution Phases	Weight Fraction
SiO_2	54.63	63.19	74.65	63.21	−0.02	Pl	−0.25
Al_2O_3	17.27	15.26	11.57	15.42	−0.15	Cpx	−0.16
FeO*	7.13	6.25	3.55	6.25	0.00	Opx	−0.03
MgO	4.31	1.47	1.3	1.43	0.05	Mt	−0.1
CaO	8.66	3.98	1.75	3.95	0.02	schist	0.46
Na_2O	3.66	3.83	2.66	3.11	0.71	Dhtr	1.01
K_2O	1.64	3.25	2.78	2.79	0.46		
TiO_2	1.19	1.27	0.57	1.31	−0.04		
P_2O_5	0.37	0.41	0.08	0.4	0.01		
MnO	0.13	0.1	0.07	0.15	−0.05	r^2	0.75
	Model 2: Andesite to High-Silica Andesite						
	Parent 81ML1	Daughter 81ML5	Contaminant[b]	Calculated Daughter	Residuals	Solution Phases	Weight Fraction
SiO_2	56.87	63.19	68.72	63.19	0	Pl	−0.225
Al_2O_3	16.4	15.26	13.43	15.54	−0.27	Cpx	−0.118
FeO*	6.79	6.25	5.26	6.25	0	Opx	−0.109
MgO	5.00	1.47	2.55	1.46	−0.01	Mt	−0.003
CaO	7.16	3.98	3.22	3.97	0.01	schist	0.684
Na_2O	3.38	3.83	2.43	2.81	1.02	Dhtr	1.23
K_2O	1.86	3.25	2.51	2.82	0.43		
TiO_2	1.11	1.27	0.67	1.19	0.08		
P_2O_5	0.31	0.41	0.11	0.31	0.1		
MnO	0.1	0.1	0.08	0.1	−0.01	r^2	1.32

Major elements in wt %. Pl, Plagioclase; Cpx, clinopyroxene; Opx, orthopyroxene; Mt, magnetite Dhtr, daughter; r^2, sum of the residual squared.
[a]Average of four schists.
[b]Average of terrane.

TABLE 8. Summary of Trace Element Model Calculations for Nowitna Andesites Using Partition Coefficients of *Gill* [1981]

	Model 1								
Trace Elements, ppm	Parent 75Ch67	Assimilant Four Schists[a]	Daughter	Calculations $F = 0.60$	Calculations $F = 0.55$	Calculations $F = 0.50$	Partition Coefficient	Residue at $F = 0.55$,[b] ppm	Percent Residue[c]
Rb	50	101.3	89	115	130	145	0.15	−41	−31.54
Ba	846	753.5	1510	1495	1640.5	1786	0.2	−131	−7.95
Ce	54.5	69.5	91	91	98.5	106	0.39	−7.5	−7.61
Sc	19.5	7.8	16.6	16	15.5	15	1.02	1.1	7.10
Co	25.8	6.7	10.5	11	9.5	8	1.8	1	10.53
Zr	199	315.8	290	411	458.5	506	0.19	−169	−36.75
	Model 2								
Trace Elements, ppm	Parent 81ML1	Assimilant Average Metamorphic[a]	Daughter	Calculations $F = 0.60$	Calculations $F = 0.55$	Calculations $F = 0.50$	Partition Coefficient	Residue at $F = 0.55$,[b] ppm	Percent Residue[c]
Rb	48	95.5	89	113	128.5	144	0.11	−39.5	−30.74
Ba	920	545.9	1510	1433	1543.5	1654	0.27	−33.5	−2.17
Ce	60	58.6	91	95	102	109	0.37	−11	−10.78
Sc	19.7	15.2	16.6	17	16	16.	1.15	0.6	3.75
Co	23.5	14.6	10.5	11	10	9	1.9	0.5	5.0
Zr	177	271.2	290	369	413	457	0.16	−123	−29.78

[a]Assimilants are four schists, average of four quartz-mica schists from the metamorphic borderlands; average metamorphic, average of 13 analyses from the metamorphic borderlands including two metagabbros.
[b]Residue in ppm is the difference between the composition of the daughter and the model at $F = 55$. Negative numbers denote concentrations in the model greater than concentrations in the daughter; positive numbers denote concentrations in the model less than concentrations in the daughter.
[c]Residue in percent is the difference between the composition of the daughter and the model given as a percent of the composition of the daughter.

chemically and isotopically evolved composition of the Sischu rocks indicate that there has been crustal involvement in their genesis: either by crustal contamination of mantle-derived parent magmas or by direct partial melting of crustal rocks. Two types of crustal rocks underlie the volcanic field at the surface and are presumed to form the basement in this part of western Alaska: Quartz-mica schists of Precambrian age and Paleozoic carbonate rocks. Although the Sischu rocks have initial $^{87}Sr/^{86}Sr$ = 0.7075–0.7079, close to the value expected in carbonate rocks, none of the andesites or rhyolite have major or trace element compositions that would indicate they formed by direct partial melting of Paleozoic carbonate rocks. Direct partial melting of pelitic schists is also probably not the source of the Sischu magmas because Precambrian schists generally have a $^{143}Nd/^{144}Nd$ of less than 0.5119 [see *Faure*, 1986]. A model age for source of the sample having the lowest $^{143}Nd/^{144}Nd$ from the Sischu volcanic field is 154 Ma (R^0 = 0.512638). Thus the data indicate that the Sischu rocks probably represent some type of mixture between mantle-derived magmas and crustal material. The cluster of Sischu data at about 0.7080, the value for Paleozoic carbonate rocks, favors carbonate rocks as a contaminant. However, assimilation of carbonate rocks should increase the Ca, Sr, and Mg contents of the magmas, whereas the Sischu andesite has lower Mg, Sr, Ba, Sc, Cr, and Co; higher Al, Na, K, Rb, Th, U, and Ta; and the same Ca content as a Nowitna andesite (81ML 2) that has the same SiO_2 content and erupted in an area lacking carbonate rocks.

High-silica andesites from the Sischu and Nowitna fields have very different initial $^{87}Sr/^{86}Sr$ but initial $^{143}Nd/^{144}Nd$ that is about the same, despite having both formed in areas underlain by Paleozoic or older continental crust. Assimila-

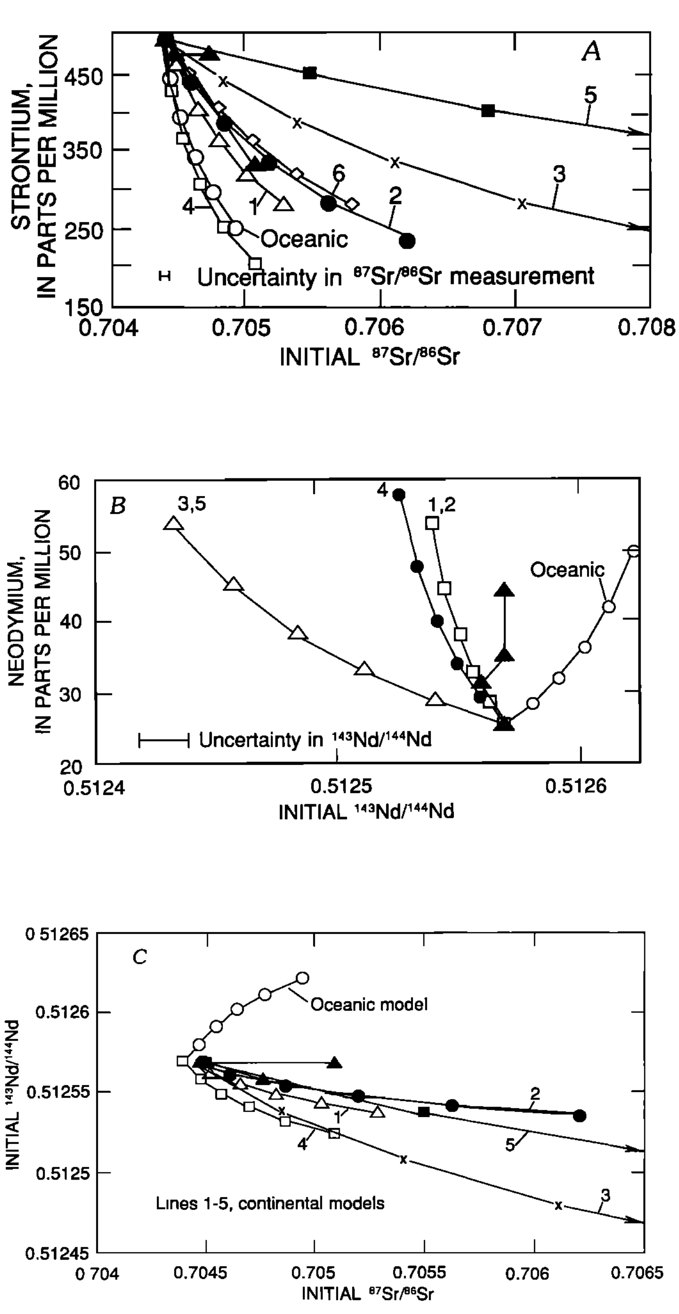


Fig. 7. (Opposite) Assimilation-fractionation models for the Nowitna volcanic field. (*a*) Sr (ppm) versus initial $^{87}Sr/^{86}Sr$; (*b*) Nd (ppm) versus initial $^{143}Nd/^{144}Nd$; and (*c*) initial $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$. Models use a low-silica andesite (sample 81ML1) having $^{87}Sr/^{86}Sr$ = 0.7044, $^{143}Nd/^{144}Nd$ = 0.51257, Sr = 498 ppm, and Nd = 26 ppm and a variety of contaminants including continental crust and seawater-hydrothermally altered oceanic crust to generate a high-silica andesite (sample 81ML5) having $^{87}Sr/^{86}Sr$ = 0.7051, $^{143}Nd/^{144}Nd$ = 0.51257, Sr = 337 ppm, and Nd = 45 ppm. Nowitna data are shown as solid triangles. Although, no $^{87}Sr/^{86}Sr$ ratios higher than 0.7046 have been measured on the oceanic terranes, seawater-hydrothermally altered oceanic crust having $^{87}Sr/^{86}Sr$ as high as 0.7080 and $^{143}Nd/^{144}Nd$ of 0.5130 was modeled to see if we could eliminate this possibility. Values for Nd (16 ppm) and Sr (190 ppm) used in the oceanic crust model are those for average Tozitna terrane (S. E. Box and W. W. Patton, Jr., unpublished data, 1988). Several compositions were modeled for continental crust: model 1 used $^{87}Sr/^{86}Sr$ = 0.7080, Sr = 350 ppm, $^{143}Nd/^{144}Nd$ = 0.5124, and Nd = 25 ppm; Model 2 used $^{87}Sr/^{86}Sr$ = 0.7200, Sr = 140 ppm, $^{143}Nd/^{144}Nd$ = 0.5124, and Nd = 25 ppm; model 3 used $^{87}Sr/^{86}Sr$ = 0.738, Sr = 140 ppm, $^{143}Nd/^{144}Nd$ = 0.5118, and Nd = 25 ppm; model 4 used $^{87}Sr/^{86}Sr$ = 0.708, Sr = 140 ppm, $^{143}Nd/^{144}Nd$ = 5124, and Nd = 25 ppm; model 5 uses $^{87}Sr/^{86}Sr$ = 0.738, Sr = 350 ppm, $^{143}Nd/^{144}Nd$ = 0.5118, Nd = 25 ppm; model 6 (Figure 7a only) uses $^{87}Sr/^{86}Sr$ = 0.710, Sr = 350 ppm. Values are from the following sources: $^{87}Sr/^{86}Sr$ = 0.7080, minimum value for Paleozoic or older crust in the area as interpreted from the isotopic composition of the Sischu volcanic rocks; $^{87}Sr/^{86}Sr$ = 0.738, value for Precambrian schist reported by *Blum et al.* [1987]; $^{87}Sr/^{86}Sr$ = 0.710–0.720, intermediate values; Sr = 140 ppm, average value for 13 metamorphic rocks from Paleozoic or older metamorphic terranes in western Alaska (Nixon Fork and Slow Fork terranes (E. J. Moll-Stalcup and M. L. Silberman, unpublished data, 1983)); Sr = 350, value for average upper continental crust given by *Taylor and McLennan* [1981]; $^{143}Nd/^{144}Nd$ = 0.5124, maximum value for Paleozoic or older rocks in the area as interpreted from the isotopic composition of the Sischu volcanic rocks; $^{143}Nd/^{144}Nd$ = 0.5118, value for rocks at the Paleozoic-Precambrian boundary (570) Ma [*Faure*, 1986, p. 231]; Nd = 25 ppm, average of 13 metamorphic rocks from Paleozoic or older metamorphic terranes in western Alaska and near the average value for upper crust given by *Taylor and McLennan* [1981]. Models 1, 2, 3, 5, and 6 and the oceanic crust model use an r (ratio of mass assimilated to mass of crystals fractionated) of 0.3; model 4 uses r = 0.4. Partition coefficients D_{Sr} = 1.55 and D_{Nd} = 0.16 are based on phenocrysts in the rocks and published K_d by *Gill* [1981]. Model lines 1, 2, and 6 give the best fit to the isotopic and elemental data, perhaps indicating that the Nowitna magmas were contaminated by isotopically moderate material having $^{87}Sr/^{86}Sr$ = 0.708–0.720, Sr = 140–350 ppm, Nd = 25 ppm, and $^{143}Nd/^{144}Nd$ = 0.5124. Model curves for oceanic crust give $^{143}Nd/^{144}Nd$ values that are too low at a given Nd content and $^{87}Sr/^{86}Sr$ values that are too high at a given Sr content. Precambrian crust, represent by lines 3 and 5, gives Sr values that are too high relative to $^{87}Sr/^{86}Sr$ and Nd contents that are too low at a given $^{143}Nd/^{144}Nd$.

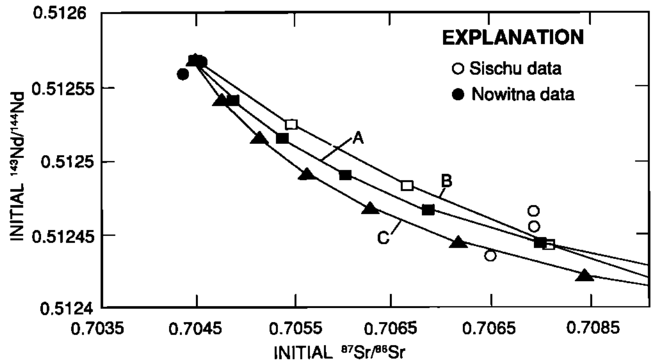


Fig. 8. Model for generating the isotopic composition of the Sischu volcanic field from the most mafic Nowitna magmas by assimilation of highly evolved crustal rocks using the equations of *DePaolo* [1981]. C_a, elemental concentration in wall rock; C_i, elemental concentration in initial magma; R_a, isotopic composition of wall rock; and R_i, isotopic composition of initial magma; r, weight ratio of cummulates to assimilated rock. Sischu data are shown as open circles. Nowitna data are shown as solid circles. Three curves were calculated: Curve A (solid squares) uses $C_{a_{Sr}}$ = 140 ppm, $R_{a_{Sr}}$ = 0.735, $C_{i_{Sr}}$ = 500 ppm, $R_{i_{Sr}}$ = 0.70445, $C_{a_{Nd}}$ = 25 ppm, $R_{a_{Nd}}$ = 0.5119, $C_{i_{Nd}}$ = 26 ppm, $R_{i_{Nd}}$ = 0.51257 for Nd; curve B (open squares) uses the same parameters as curve A except $C_{a_{Sr}}$ = 350 ppm and $R_{a_{Nd}}$ = 0.5115; curve C (triangles) uses the same parameters as curve A except $C_{a_{Sr}}$ = 104 ppm. D_{Nd} = 0.16 and D_{Sr} = 1.55 for all models. Description of parameters are the same as in Figure 7 except $R_{a_{Nd}}$ values 0.5115–0.5119 are values for Precambrian rocks, and $C_{a_{Sr}}$ = 104 is the value from Precambrian schist reported by *Blum et al.* [1987].

tion-fractionation calculations [*DePaolo*, 1981] show that high-silica andesites from the two fields can be generated from compositionally similar parent magmas by different amounts of assimilation if the Sischu magmas assimilate continental crust that is more isotopically evolved ($^{87}Sr/^{86}Sr$ = 0.735; $^{143}Nd/^{144}Nd$ = 0.5118) than the Nowitna andesites ($^{87}Sr/^{86}Sr$ = 0.7080; $^{143}Nd/^{144}Nd$ = 0.5124) (Figure 8). The Sischu rhyolites, however, have the same isotopic composition as the Sischu andesites and do not indicate further contamination by high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ country rock.

The Sischu rhyolites have low HREE concentration and high LREE contents. REE patterns like these can be produced by fractionation of garnet, hornblende, or zircon or partial melting of sources having these minerals in the residue. If we assume that the rhyolites fractionated from the isotopically identical andesites, then zircon probably did not precipitate in significant amounts because Zr contents are lower in the andesite (176 ppm) than in the rhyolites (226–418 ppm). Rayleigh fractionation calculations using the high-silica andesite as the starting magma suggest that 25–40% hornblende or 2–25% garnet must have fractionated from the andesite to produce the Ce and Yb patterns of the rhyolites. Calculations based on selected trace elements (Nb, Yb, Ce, Co, Cr, and Sc) suggest that hornblende rather than garnet is the dominant fractionating phase (Figure 9). However, crystal fractionation calculations using the major element data [*Stormer and Nicholls*, 1978; *Geist et al.*, 1985] were not successful in modeling the data, probably because the major element data do not reflect magma compositions due to alteration of the alkali elements and because the magmas do not represent one liquid line of ascent.

Alternatively, the rhyolites may have formed by partial melting of Paleozoic crustal rocks having an $^{87}Sr/^{86}Sr$ of 0.708 and a $^{143}Nd/^{144}Nd$ of 0.5125 if such potential source rocks occur in the little known Minchumina terrane. A third possibility is that the Sr isotopic ratios of the Sischu magmas were altered by hydrothermal alteration of fluids containing considerable dissolved Sr derived from the Paleozoic carbonate rocks of the Nixon Fork and Minchumina terranes. The rhyolites have low Sr contents and their Sr isotopic composition is easily modified. The andesite, however, has 408 ppm Sr and would require much greater water/rock ratios to modify its isotopic composition, yet it has the same isotopic composition as the rhyolites.

In summary, the Nowitna suite, which ranges from basaltic andesite to high-silica andesite, probably evolved by contamination of mantle-derived magmas by crustal assimilants of probable Paleozoic age having $^{87}Sr/^{86}Sr$ = 0.708–0.720 and $^{143}Nd/^{144}Nd$ = 0.5124. The high-silica andesite in the Sischu volcanic field has much higher initial $^{87}Sr/^{86}Sr$

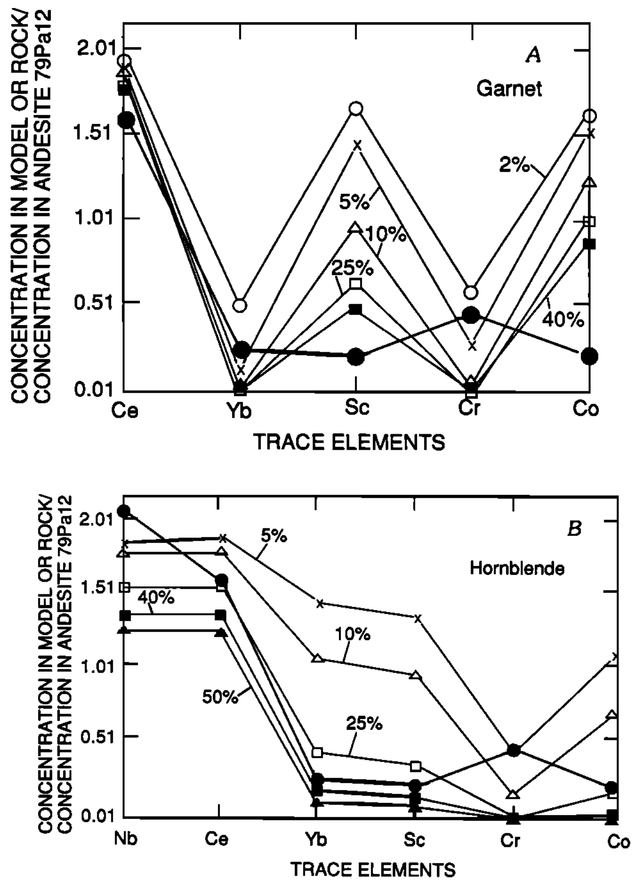


Fig. 9. Trace element models for the Sischu volcanic field. Two models were calculated: (*a*) one for fractionation of various proportions of garnet and (*b*) one for fractionation of various proportions of hornblende. Both models use the composition of the andesite (sample 79Pa12) as the starting magma and rayleigh fractionation to generate a typical rhyolite (sample 77Pa202). Fractionation of 2% magnetite was added to the calculations for Cr, Sc, Co, and Nb. Actual data for the rhyolite, normalized to the andesite composition, are shown by the solid circles. All calculated values are normalized to the composition of the starting andesite. Fractionation of either 8% garnet or 30% hornblende can account for the REE data (Ce and Yb), but hornblende fractionation fits the Sc, Cr, and Co data better than garnet fractionation. Partition coefficients used in the calculation are from *Nagasawa and Schnetzler* [1971] (hornblende 3Hb), *Schnetzler and Philpotts* [1970] (garnet GSFC218), and *Gill* [1981].

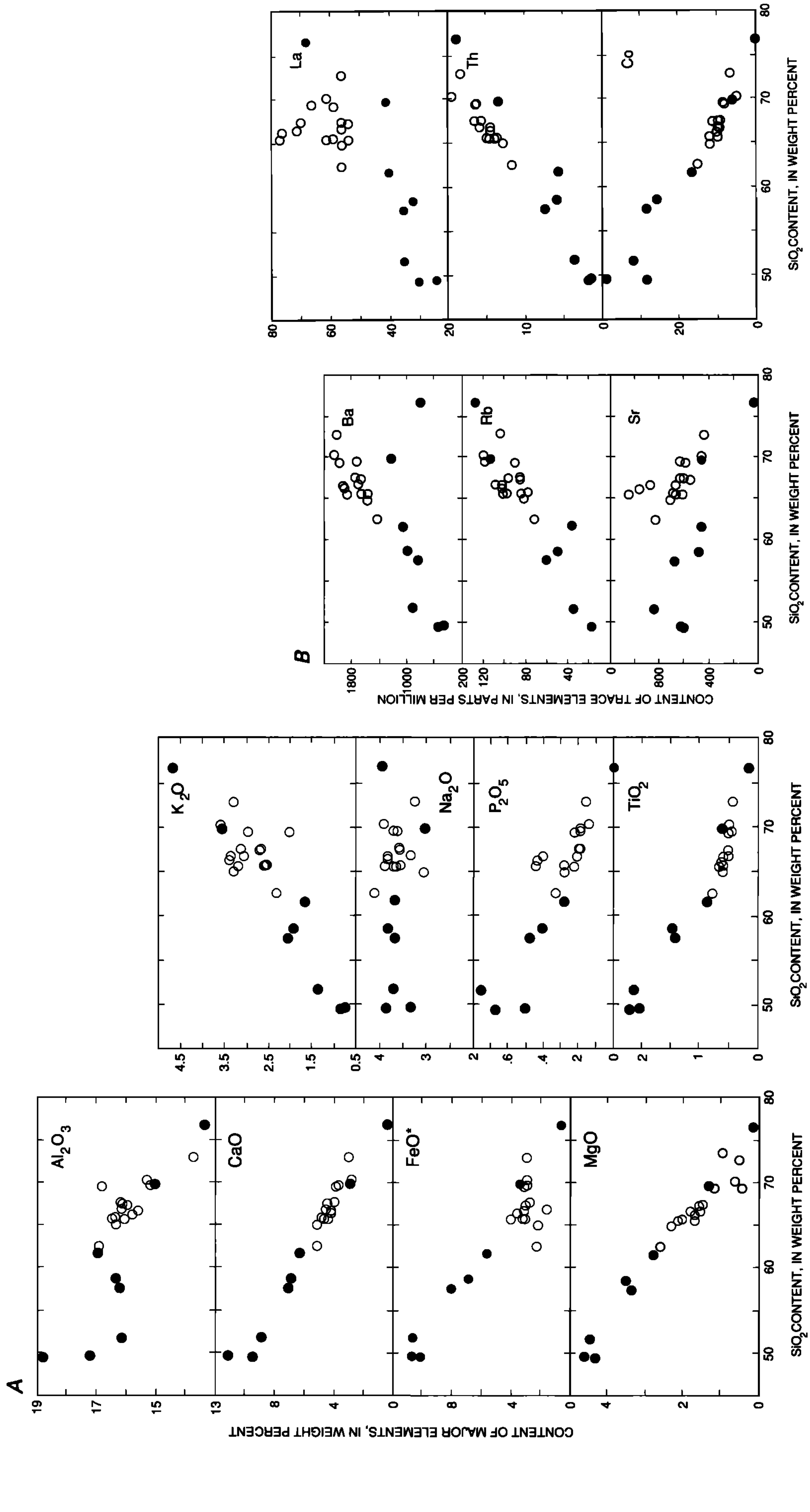


Fig. 10. Variation of (*a*) major and (*b*) trace elements with SiO_2 for the Kanuti (open circles) and Yukon River (solid circles) volcanic field.

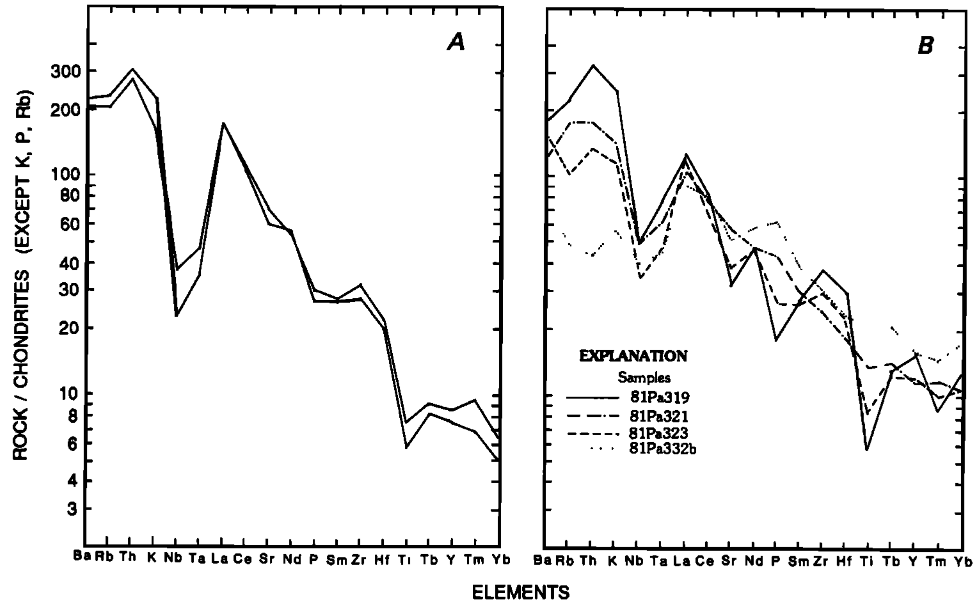


Fig. 11. Spidergrams for typical dacites from (*a*) the Kanuti volcanic field and (*b*) the Yukon River area. An anorogenic basalt (sample 81Pa332b) from the Yukon River area shows small Nb-Ta depletions and no alkali enrichment relative to La, but all andesites and dacites show significant alkali enrichment and Nb-Ta depletion relative to La. Normalizing values from *Thompson* [1982].

(0.7080) than the Nowitna samples and probably originated by contamination of either more crust or more evolved crust. Differences in Sr and Nd isotopic composition between the two fields may be due in part to differences in the age or composition of the underlying lithosphere. The Nixon Fork terrane, which underlies parts of both fields, has a minimum age of 1200 Ma, whereas the oldest reported ages in the part of the Ruby terrane that underlies the western part of the Nowitna volcanic field, are 400–500 Ma [*Patton et al.*, 1989]. Thus the isotopic difference between the two volcanic fields may be due to differences in the age of the underlying mantle or crust.

VOLCANIC FIELDS IN THE YUKON-KOYUKUK PROVINCE

Chemistry, Mineralogy, and Isotopic Composition

The volcanic and intrusive rocks in the Blackburn Hills span the compositional range basalt, andesite, rhyolite, and granodiorite. The volcanic rocks have between 48 and 77 wt % SiO_2, with a silica gap between 63 and 70 wt % SiO_2. Samples from the granitic pluton, in the center of the field, have between 62 and 72 wt % SiO_2 and plot in the gap defined by the volcanic data. Seventeen analyzed samples from the Kanuti volcanic field are dominantly dacite but range from high-silica andesite (62 wt % SiO_2) to rhyolite (73 wt % SiO_2). The volcanic rocks in the Yukon River area consist of a wide variety of lithologies, including calc-alkalic andesite, dacite, and rhyolite and mildly alkalic basalt and latite, and range in silica from 48 to 77 wt % SiO_2.

Almost all of the rocks from all three areas are moderate to high-K calc-alkalic on the basis of chemistry (felsic samples cross into the extrapolated high-K field of *Gill* [1981] at about 60 wt % SiO_2). Most plot in the subalkaline field on a total alkalis versus SiO_2 diagram, with the exception of some of the intrusive and high-silica rocks which extend into the alkalic field. Suites from all three areas lack Fe enrichment and are calc-alkalic as defined by trends of CaO and total alkalis versus SiO_2.

The Blackburn Hills (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989), Kanuti, and Yukon River data show typical calc-alkalic trends on Harker diagrams. CaO, FeO*, TiO_2, Al_2O_3, and MgO contents decrease with increasing SiO_2 (Figure 10 and E. J. Moll-Stalcup and J. G. Arth (manuscript in preparation, 1989). K_2O contents increase with SiO_2 for Yukon River and Blackburn Hills rocks and show considerable scatter for the Kanuti rocks. Trace element trends with SiO_2 are not as straightforward. Kanuti data show some scatter with Sr and Co decreasing as SiO_2 increases and Ba, Rb, and Th increasing as SiO_2 increases (Figure 10). La shows two groups, one that decreases with SiO_2 and one that remains about constant (Figure 10). Eu, Sc, Co, and Sr decrease and Th, Ta, Hf, and Rb increase with increasing SiO_2 for the Yukon River rocks (Figure 10 and Table 4). La, Ce, and Nb increase slightly from 49 to 70% SiO_2 and then increase more rapidly from dacite to rhyolite (Table 4).

Most of the rocks from the Blackburn Hills, Yukon River, and Kanuti fields have compositions and mineralogies that are typical of arc volcanic rocks, but some of the youngest rocks show postsubduction affinities. Most of the rocks are enriched in Ba, Rb, Th, K, and Sr and depleted in Nb and Ta relative to La (Figure 11), similar to arc volcanic rocks. Mineral assemblages in most rocks are also characteristic of calc-alkalic island arcs and orogenic continental margins [*Ewart*, 1979; *Gill*, 1981]. Typical basalts have phenocrysts of plagioclase, clinopyroxene, olivine, and magnetite in a mineralogically similar groundmass. Andesites from the Blackburn Hills and Yukon River fields have phenocrysts of plagioclase, clinopyroxene, and magnetite, plus or minus orthopyroxene; and high-silica andesites have plagioclase, clinopyroxene, hornblende, and magnetite. Low-silica dacites (less than 67% SiO_2) from the Kanuti field have

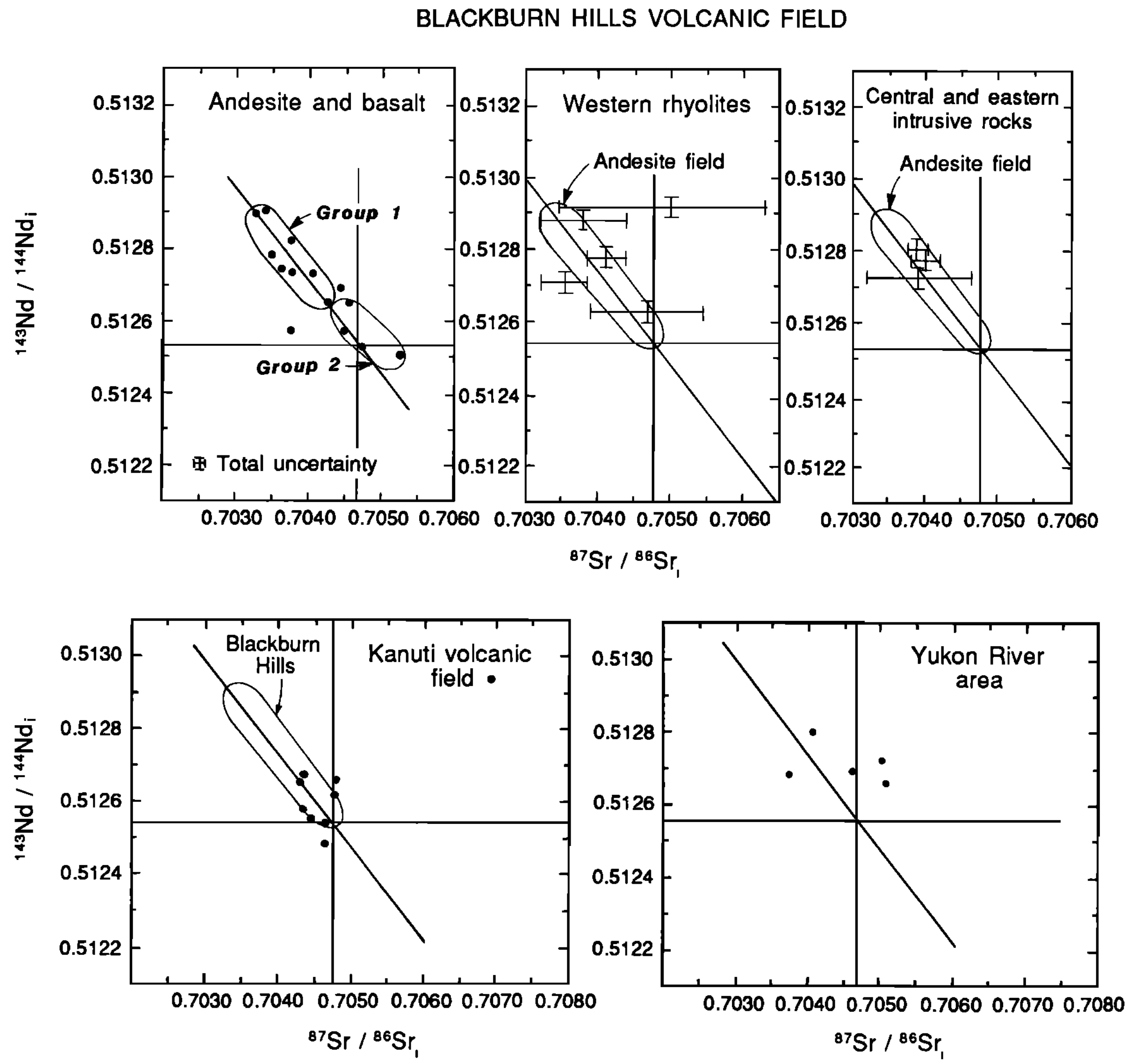


Fig. 12. Initial $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ data for volcanic fields in the Yukon-Koyukuk province. Error bars show total uncertainties for the felsic rocks. Total uncertainties for all other rocks are shown by the small cross on the diagram for the Blackburn Hills basalts and andesites. Lines for "bulk earth" at 56 and 60 Ma were calculated using the values given by *Allegre et al.* [1983] and are as follows: 56 Ma, $^{87}Sr/^{86}Sr = 0.70469$, $^{143}Nd/^{144}Nd = 0.51255$; 60 Ma, $^{87}Sr/^{86}Sr = 0.70468$, $^{143}Nd/^{144}Nd = 0.51254$.

oligoclase-andesine, hornblende, magnetite, orthopyroxene, and clinopyroxene; and dacites from the Yukon River field have plagioclase, quartz, hornblende, clinopyroxene, and magnetite. Rhyolites from the Kanuti field have oligoclase, quartz, hornblende, magnetite, and rhyolites from the Blackburn Hills field have plagioclase plus or minus biotite plus or minus hornblende.

Rocks having postsubduction affinities include some of the Eocene rocks in the Blackburn Hills and Yukon River area that have compositions or mineral assemblages that are more characteristic of the bimodal basalt-rhyolite or oceanic island association than calc-alkalic continental margins [*Ewart*, 1979; *Gill*, 1981]. These include young (post-56 Ma) basalts and mildly alkalic rhyolites from the Blackburn Hills field and basalts, latites, and mildly alkalic rhyolites from the Yukon River area. The basalts in the Blackburn Hills, which overlie rhyolites dated at 56 Ma, are not enriched in alkali and alkaline earth elements nor depleted in Nb-Ta relative to La (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989). The basalt in the Yukon River area has groundmass olivine and biotite, groundmass minerals that are atypical of orogenic rocks. It also contains too much TiO_2 (2.2%) to be classified as an orogenic basalt and is not enriched in alkalis relative to La (sample 332b, Figure 11). The mildly alkalic rhyolites in the Blackburn Hills have high-sodium and low-potassium contents and phenocrysts of unzoned anorthoclase and Fe-rich hedenbergite. The high-soda/low-potash rhyolites are chemically similar to rocks from the Deception Island, Fedarb Island, St. Andrew Strait, and Papua New Guinea [*Ewart*, 1979], and according to *Ewart* [1979, p. 43] occur in areas where "subduction has ceased in the relatively recent geologic past." Single unzoned feldspars of anorthoclase occur on oceanic islands and in the bimodal association [*Ewart*, 1979]. The latites and mildly alkalic rhyolites in the Yukon River area have phenocrysts of oligoclase, anorthoclase, sanidine, and biotite, hornblende and plagioclase, anorthoclase, sanidine, and quartz, respectively. Feldspars zoned from plagioclase to anorthoclase and sanidine are uncommon in rhyolitic rocks but have been reported on Iceland [*Sigurdson*, 1971].

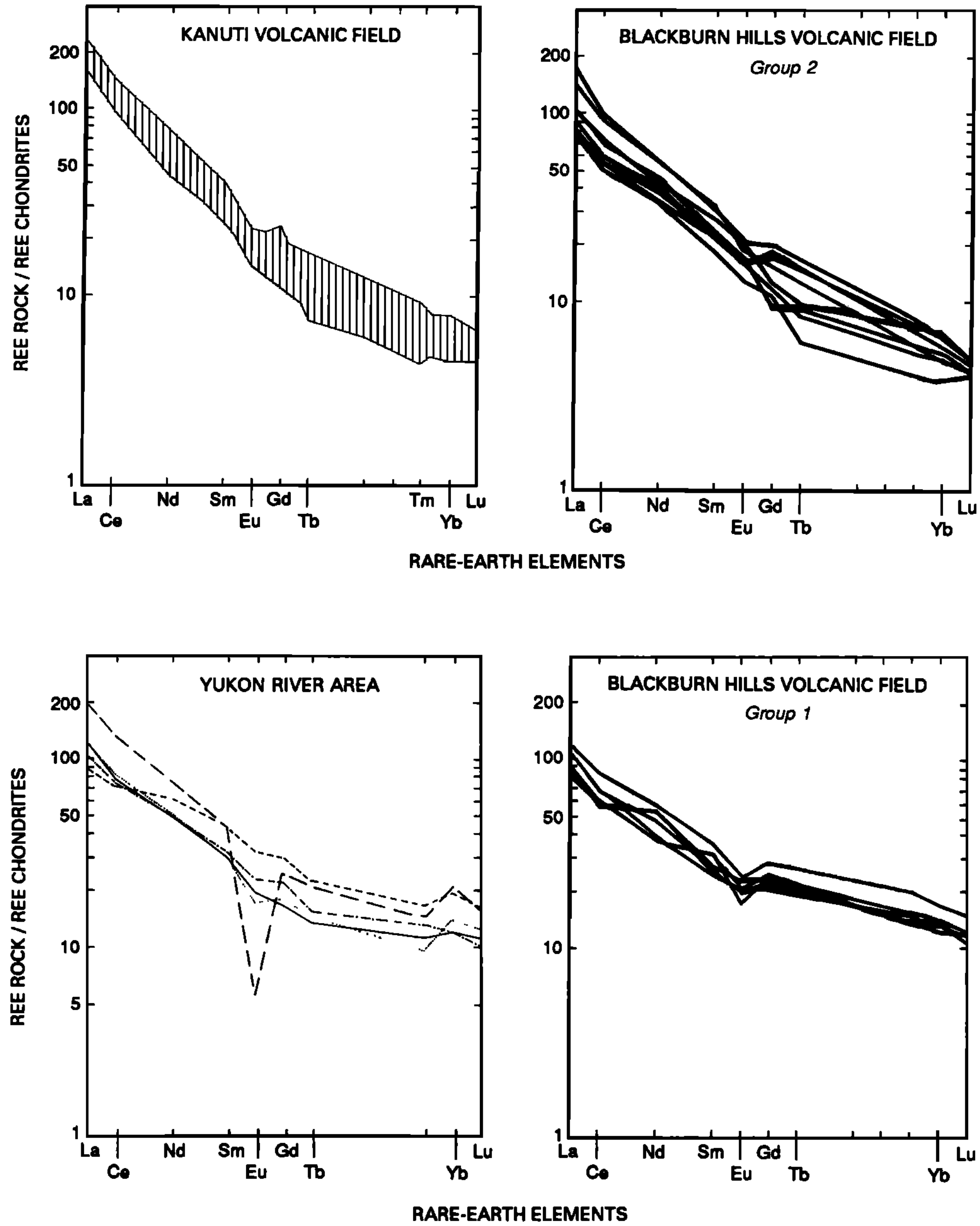
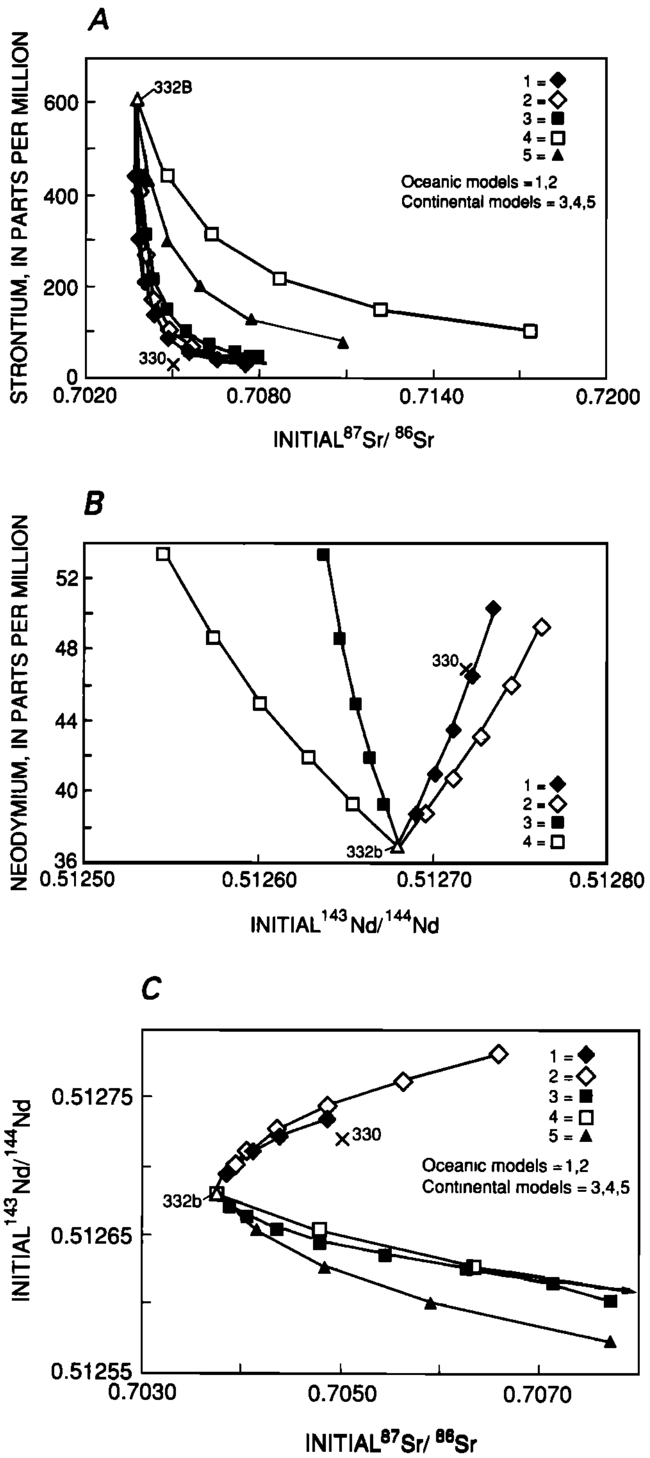


Fig. 13. REE patterns for volcanic fields within the Yukon-Koyukuk province. Rhyolite from the Yukon River area has the large Eu anomaly.

All of these mildly alkalic rocks are 56 Ma or younger and overlie or are interbedded with rocks having typical orogenic compositions and mineralogies. The presence of these mildly alkalic rocks is interpreted as marking the end of subduction-related magmatism and the transition to intraplate magmatism in this part of western Alaska [*Moll-Stalcup*, 1989]. All the older rocks, and some of the post-56 Ma rocks, have typical orogenic compositions.

Some of the rocks from the Kanuti field and the Yukon River area show disequilibrium mineralogies or textures. In the Kanuti field these include quartz phenocrysts/xenocrysts in a rock having 65% SiO_2 or plagioclase phenocrysts with sieve-textured cores or rims. In addition, one rock from the Kanuti field has a xenolith of sillimanite-spinel schist and one contains a single xenocryst of andalusite. One rock from the Yukon River area has plagioclase phenocrysts having both cores and sieve-textured mantles of oligoclase which are rimmed by a thin band that is reversely zoned from andesine to labradorite, perhaps indicating mixing with more mafic magma or contamination by mafic material.

The Blackburn Hills rocks show the largest range in initial $^{87}Sr/^{86}Sr$ and initial $^{143}Nd/^{144}Nd$ of any of the volcanic fields studied. Data on the basalts and andesites plot within the oceanic "mantle array" and extend from $(^{87}Sr/^{86}Sr)_i$ = 0.7033 and $(^{143}Nd/^{144}Nd)_i$ = 0.5129 to $(^{87}Sr/^{86}Sr)_i$ = 0.70524 and $(^{143}Nd/^{144}Nd)_i$ = 0.51253 (Figure 12). They are isotopically similar to Andean volcanic rocks from southern Chile in the southern volcanic zone [*Hickey et al.*, 1984]. The basalts and andesites are divided into two groups on the basis of elemental and isotopic composition (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989). Group 1 consists of basalts and andesites (48–61 SiO_2) that are moderately LREE-enriched and have HREE of 10–20× chondrites, initial $^{87}Sr/^{86}Sr$ less than 0.7043, and initial $^{143}Nd/^{144}Nd$ greater than 0.5127 (Figures 12 and 13). Group 2 consists of andesites (58–63% SiO_2) having steeper REE patterns, HREE about 5–7× chondrites, initial $^{87}Sr/^{86}Sr$ greater than 0.7044, and initial $^{143}Nd/^{144}Nd$ less than 0.5127 (Figures 12 and 13). Group 1 rocks show a strong correlation between isotopic composition and SiO_2; basalts have the lowest initial $^{87}Sr/^{86}Sr$ and highest initial $^{143}Nd/^{144}Nd$, and high-silica andesites have the highest initial $^{87}Sr/^{86}Sr$ and



lowest initial $^{143}Nd/^{144}Nd$ (Figure 12). Group 1 rocks occur throughout the field; in contrast all the group 2 samples that we collected were from a single ridge in the northwestern part of the volcanic field. Rhyolite domes, which occur at the top of the stratigraphic section, show a similar, but smaller range in initial $^{87}Sr/^{86}Sr$ and initial $^{143}Nd/^{144}Nd$ than the group 1 basalts and andesites (Figure 12). The central granitic pluton and the small intrusive bodies along the eastern side of the field show much less variation and have intermediate $(^{87}Sr/^{86}Sr)_i$ and $(^{143}Nd/^{144}Nd)_i$ compositions that plot within the field for group 1 andesites (Figure 12).

The Kanuti volcanic rocks (62–73% SiO_2) are similar to group 2 andesites from the Blackburn Hills volcanic field in their REE patterns and isotopic composition (Figures 12 and 13). Initial $^{87}Sr/^{86}Sr$ and initial $^{143}Nd/^{144}Nd$ values plot near "bulk earth" at 56 Ma. Initial $^{87}Sr/^{86}Sr$ do not correlate with initial $^{143}Nd/^{144}Nd$, Rb/Sr, or major or trace element chemistry, nor do they correlate with location or age. The two samples having the highest initial $^{87}Sr/^{86}Sr$ contain inclusions of schist, and their high initial $^{87}Sr/^{86}Sr$ at a given initial $^{143}Nd/^{144}Nd$ may be due to assimilation of small amounts of Paleozoic or older continental crust, if the assimilation was accompanied by plagioclase fractionation such that $^{87}Sr/^{86}Sr$ increased with little change in $^{143}Nd/^{144}Nd$.

Basalts and andesites from the Yukon River area have REE patterns that are similar to group 1 andesites from the Blackburn Hills, with LREE about 70–120× chondrites, HREE about 11–14× chondrites, and a small or nonexistent negative Eu anomaly (Figure 13). The shape of the pattern for one sample of dacite is similar to that of the more mafic rocks but has a larger Eu anomaly. The rhyolite at Eagle Slide has LREE about 200 and HREE about 15× chondrites, and a large negative Eu anomaly (Figure 13).

A basalt, dacite, rhyolite, and two andesites from the Yukon River volcanic rocks were analyzed for Sr and Nd isotopes. Four of the five samples have similar initial $^{143}Nd/^{144}Nd$ (0.51266–0.51272) but initial $^{87}Sr/^{86}Sr$ that varies from 0.7037 to 0.7050 (Figure 14). The fifth sample, an andesite (81Pa 323), has higher initial $^{143}Nd/^{144}Nd$ (0.51280) and moderate initial $^{87}Sr/^{86}Sr$ (0.7041) and plots near the "mantle array" within the field for group 1 rocks from the

Fig. 14. (Opposite) Assimilation-fractionation calculations for the Yukon River volcanic rocks. Model uses a basalt (81Pa332b) having initial $^{87}Sr/^{86}Sr$ = 0.70374, initial $^{143}Nd/^{144}Nd$ = 0.51268, Nd = 37 ppm, and Sr = 603 ppm for the starting magma and calculates assimilation-fractionation curves for two types of assimilant, continental crust and seawater-altered oceanic crust. Bulk D_{Nd} = 0.5, and bulk D_{Sr} = 3 for all the models. Tick marks are shown at 10% fractionation intervals or intervals of F = 0.1. Curves 1 and 2 are for oceanic assimilants: Curve 1 uses r = 0.3; curve 2 uses r = 0.4. Elemental values for oceanic crust (16 ppm Nd, 190 ppm Sr) are values for an average of seven samples from the Angayucham/Tozitna terrane; isotopic values ($^{87}Sr/^{86}Sr$ = 0.7080, $^{143}Nd/^{144}Nd$ = 0.5132) are those for typical seawater-altered MORB [*McCulloch et al.*, 1981]. Elemental and isotopic values for continental crust (25 ppm Nd, 140–350 ppm Sr, $^{87}Sr/^{86}Sr$ = 0.7080–0.738; $^{143}Nd/^{144}Nd$ = 0.5118–0.51245) are the same as those given in Figure 7. Parameters for continental contamination models are curve 3, $C_{a_{Sr}}$ = 350 ppm, $R_{a_{Sr}}$ = 0.708, $C_{a_{Nd}}$ = 25, $R_{a_{Nd}}$ = 0.5124; curve 4, $C_{a_{Sr}}$ = 350 ppm, $R_{a_{Sr}}$ = 0.738, $C_{a_{Nd}}$ = 25, $R_{a_{Nd}}$ = 0.5118; curve 5, $C_{a_{Sr}}$ = 140 ppm, $R_{a_{Sr}}$ = 0.738, $C_{a_{Nd}}$ = 25, $R_{a_{Nd}}$ = 0.5118. The oceanic crust curves fit the data best, chiefly because the rhyolite has slightly higher initial $^{143}Nd/^{144}Nd$ than the basalt.

Blackburn Hills (Figure 12). It is from the south end of the Poisen Creek volcanic field and is one of the youngest rocks we analyzed (49 Ma).

Origin and Evolution of the Blackburn Hills, Kanuti, and Yukon River Magmas

The Blackburn Hills magmas have isotopic compositions that plot within the "mantle array," overlapping with values for oceanic islands and some intraoceanic island arcs. K/Rb (436), La/Yb (8.9), Hf/Th (1.44), and Y/Zr (0.13) ratios for Blackburn Hills basalts are more indicative of an OIB-type (oceanic island basalt type), than a MORB-type (mid-ocean ridge basalt type) mantle source (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989). The basalts also have Ba/La (19), Ba/Th (161), and La/Nb (1.25) ratios that are indicative of a small, but significant subduction component, i.e, contribution from the subducted slab and/or sediments [see *Gill*, 1981; *Perfit and Kay*, 1986; *Arculus and Powell*, 1986]. E. J. Moll-Stalcup and J. G. Arth (manuscript in preparation, 1989) interpret the source of the group 1 basalts as being an OIB-type mantle that has been metasomatized by the addition of a small but significant subduction component. The mantle source of these basalts must have had a maximum $^{87}Sr/^{86}Sr$ of 0.7033 and a minimum $^{143}Nd/^{144}Nd$ of 0.5129: contamination by continental material, in the form of subducted sediments or assimilated crust, would shift the isotopic composition of the basalts toward higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$. The more primitive isotopic composition of late Tertiary Bering Sea basalts, which have $^{87}Sr/^{86}Sr = 0.7027$ and $^{143}Nd/^{144}Nd = 0.5130$ [*Moll-Stalcup*, 1989], may therefore more closely represent the isotopic composition of asthenospheric mantle in this area. If this is the case, then the subduction component must be derived, at least in part, from enough subducted terrigenous sediments to lower the $^{143}Nd/^{144}Nd$ of the source by 0.0001. Andesites from group 1 have higher Ba/La (38), La/Nb (2.6), and initial $^{87}Sr/^{86}Sr$ and lower initial $^{143}Nd/^{144}Nd$, which could indicate either the addition of an increasingly larger subduction component to the mantle source of these rocks or assimilation of lower crust of the island arc Koyukuk terrane by mantle-derived basalts as they rise and fractionate. These Blackburn Hills group 1-type magmas were not found elsewhere in our studies, with the exception of one andesite (81Pa323) from the Yukon River area, which has similar $(^{87}Sr/^{86}Sr)_i$ (0.70407), $(^{143}Nd/^{144}Nd)_i$ (0.51280), and REE contents.

Group 2 rocks from the Blackburn Hills are interpreted as partial melts of the lower crust of the Koyukuk terrane, which is presumed to range in composition from island-arc tholeiitic to calc-alkalic to shoshonitic [*Box and Patton*, this issue]. Early Cretaceous shoshonites of the Yellow River area, which were erupted at about 120 Ma, possibly during arc-continent collision [*Patton and Moll*, 1985; *Box and Patton*, this issue], have $^{87}Sr/^{86}Sr = 0.7075$ and $^{143}Nd/^{144}Nd = 0.51248$ (S. C. Bergman, personal communication, 1986), values even more isotopically evolved than group 2 andesites ($(^{87}Sr/^{86}Sr)_i$ = 0.70442–0.70524 and $(^{143}Nd/^{144}Nd)_i$ = 0.51250–0.51269) and Kanuti dacites ($(^{87}Sr/^{86}Sr)_i$ = 0.70431–0.70477 and $(^{143}Nd/^{144}Nd)_i$ = 0.51248–0.51267). Partial melts of the lower crust of the Koyukuk terrane may have the appropriate isotopic composition of the shoshonitic parts of the terrane were involved in the melting. To produce the steep REE patterns and low HREE contents of the group 2 rocks, we propose that their lower crustal source contain residual garnet or amphibole.

One andesite sample from the Blackburn Hills has low REE abundances and plots in the low $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ field on a $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ diagram (Figure 12). The isotopic composition of this sample may represent a source in a sliver of early Paleozoic lower crust of the Ruby terrane, or mixing between old lower crust and group 1 rocks. This rock has higher MgO, CaO, Cr, and Al_2O_3 and lower FeO*, Ba, Th, Nb, Ta, Zr, and TiO_2 than other andesites from the Blackburn Hills.

Rhyolites from the Blackburn Hills have isotopic compositions that overlap with values for the basalts and andesites, and E. J. Moll-Stalcup and J. G. Arth (manuscript in preparation, 1989) interpret them as crystal fractionates of these more mafic rocks. Fractionation at crustal levels within isotopically evolved crust might involve assimilation and pull the composition of the rhyolites off the "mantle array" into the high $^{87}Sr/^{86}Sr$ field. Most of the rhyolites plot within the "mantle array" on a Sr-Nd diagram indicating that fractionation of these felsic magmas either did not take place at crustal levels, within the stability field for plagioclase, or did not involve assimilation of crustal rocks having Sr and Nd isotopic compositions that were significantly different from that of the magmas (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989). All of the Blackburn Hills rhyolites have strongly negative Eu anomalies (Eu*/Eu = 2.25–7.05), indicating that plagioclase was probably a fractionating phase. Rhyolites having such primitive isotopic compositions are uncommon, and where they occur (Andes, Mexico), they are usually interpreted as fractionates of more mafic rocks that have not assimilated significant amounts of old continental crust [*Hickey et al.*, 1984; *Cameron and Cameron*, 1985; *Ferriz and Mahood*, 1987]. Alternatively, the rhyolites may represent partial melting of the crust in the Koyukuk terrane. The central pluton and eastern intrusive rocks in the Blackburn Hills also have primitive isotopic compositions and are interpreted as either fractionates of isotopically similar group 1 andesites or partial melts of young mafic to intermediate crust (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989). The relatively primitive isotopic composition of all of the felsic rocks, including both extrusive and intrusive rocks, is strong evidence for the lack of high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ wall rocks, such as old continental crust, in the vicinity of the volcanic field (E. J. Moll-Stalcup and J. G. Arth, manuscript in preparation, 1989).

Large volumes of dacite magma probably form by fractionation of more mafic magmas or partial melting of mafic rocks. The isotopic and elemental composition of the Kanuti volcanic rocks is similar to the Blackburn Hills group 2 andesites except that the Kanuti rocks are more felsic and have higher LREE contents (Figure 13 and Table 9). The data are compatible with an origin of the Kanuti suite by either crystal fractionation of more mafic arc magmas or partial melting of the lower crust of the Koyukuk terrane if the lower crust is compositionally similar to the late Paleozoic and Mesozoic andesitic volcanic rocks exposed at the surface. At lower crustal pressures we assume these rocks would be metamorphosed to granulite or amphibolite facies assemblages. Granulite- or amphibolite-facies mafic to intermediate rock (compositionally equivalent to typical Koy-

TABLE 9. Comparison of Hornblende High-Silica Andesites From the Blackburn Hills and Kanuti Volcanic Fields

	Blackburn Hills 80ML12A	Kanuti 81ML315B
SiO_2	62.1	62.4
Al_2O_3	17.2	16.9
FeO*	5.21	5.15
MgO	2.26	2.58
CaO	4.14	5.19
Na_2O	4.73	4.09
K_2O	2.47	2.32
TiO_2	0.95	0.78
P_2O_5	0.41	0.33
MnO	0.04	0.09
Rb	76	72.
Sr	696.	832.
Ba	1733.	1430.
La	56.	56.
Eu	1.41	1.38
Yb	1.25	1.4.
Hf	4.4	4.4
Nb	24.	13.
Ta	1.53	0.93
Th	13.9	11.6
Sc	9.84	10.7
Zr	198	215

ukuk terrane andesite or basalt) would probably have a mineral assemblage of about 70% plagioclase, 0–5% garnet, 0–10% hypersthene, and 15–25% hornblende. Partial melting models using two mineral assemblages were calculated for the trace elements Rb, Th, Ba, Cr, Nb, Ce, and Yb (Table 10). The trace element models require between 40 and 60% partial melting to generate magmas like those in the Kanuti volcanic field. These partial melting models are appealing because they successfully account for the extremely high-Ba contents, despite moderate-K contents, the low-HREE contents, and the restricted range in composition (62–73% SiO_2) of the Kanuti rocks.

An alternative to direct partial melting of the lower crust may be differentiation of more mafic arc magmas generated during early Tertiary subduction if these mafic arc magmas equilibrated with the lower crustal mineral assemblage as they rose to the surface. If the mafic arc magmas had very low concentration of Nb and Ta, their contribution could account for the Kanuti data. However, this model does not account for the lack of rocks having SiO_2 less than 62 wt %.

The moderate $(^{143}Nd/^{144}Nd)_i$ and $(^{87}Sr/^{86}Sr)_i$ composition of the Kanuti samples precludes involvement of significant amounts of ancient continental crust in the genesis of the volcanic rocks. Nearby Cretaceous granitic plutons that intrude continental crust of the Ruby terrane have much higher initial $^{87}Sr/^{86}Sr$ (0.7055–0.7235) and much lower initial $^{143}Nd/^{144}Nd$ (0.5115–0.5123, [*Arth et al.*, this issue]) than the Kanuti volcanic samples. However, the presence of metamorphic xenoliths in two of the Kanuti samples suggests that there may have been some contamination of the Kanuti magmas by continental crust. This contamination may have occurred by assimilation of near-surface conglomerates having metamorphic and quartz-pebble clasts and does not require the occurrence of continental schist at depth under this part of the basin. However, the occurrence of foliated sillimanite in one of the xenoliths suggests that the assimilated material was at least amphibolite facies and therefore may have come from greater depth than the nearby

TABLE 10. Selected Trace Element Models for 40, 50, and 60% Modal Partial Melting of a Typical Early Cretaceous Arc Volcanic Rock (High-K Calc-Alkalic) That Has Been Metamorphosed to Amphibolite Facies

Element	K_d	Early Creataceous Arc Volcanic (83Pa98)	$F = 0.4$	$F = 0.5$	$F = 0.6$	Kanuti Volcanics Range	Typical Sample (315b)
			Assemblage A[a]				
Ba	0.13	980	2048	1735	1441	1430–2050	1430
Th	0.03	9.4	22.3	18.2	15.3	11.6–19.5	11.6
Ce	0.2	65.5	125.8	109.4	96.3	83–129	94
Yb	3.03	1.57	0.71	0.86	0.97	0.9–1.16	1.4
Cr	6.91	250	55	63.2	74.3	61.6–9.9	44
Rb	0.06	33	75.7	62.26	52.88	72–120	72
Nb	0.25	12	22	19	17	8–15	13
Ta	0.25	0.74	1.35	1.18	1.06	0.70–1.12	0.93
			Assemblage B[b]				
Ba	0.14	980	2025	1719	1494		
Th[c]	0.05	9.4	21.9	17.9	15.2		
Ce	0.24	65.5	120.4	105.7	94.1		
Yb	1.27	1.57	1.35	1.38	1.42		
Cr	9.11	250	42.62	9.5	58.9		
Rb	0.06	33	75.7	62.26	52.88		
Nb[c]	0.39	12	18.9	17.3	15.9		
Ta[c]	0.39	0.74	1.17	1.06	0.98		

Values in ppm. K_d for all elements are the recommended values from *Gill* [1981], except hornblende K_d for Yb = 4.90. The equation $C_l = C_0/[D(1-F) + F]$ [*Schilling and Winchester*, 1967] was used to calculate values, where K_d is the mineral/melt weight distribution coefficient of a trace element, D is the bulk distribution coefficient for a given mineral assemblage and trace element, F is the weight fraction of the melt relative to the original parent, C_l is the concentration of the trace element in the derived melt, and C_0 is the concentration of the trace element in the original parent.

[a]Source mineralogy of 70% plagioclase, 15% hornblende, 10% orthopyroxene, and 5% garnet.

[b]Source mineralogy of 70% plagioclase, 20% hornblende, and 5% magnetite.

[c]No K_d data for Th, Ta, or Nb for garnet was available, so K_d of zero were assumed.

schists of the Ruby terrane, which do not have surface exposures of rocks with metamorphic grade higher than greenschist facies.

Kanuti magmas are broadly similar to some of the hornblende andesites and dacites from the Austral Volcanic Zone of the Andes [*Stern et al.*, 1984], which have a restricted range in SiO_2, low HREE, and similar isotopic compositions. However, the Kanuti magmas have much higher Ba, Sr, and La contents and lack the clear correlation between $(^{87}Sr/^{86}Sr)_i$, $(^{143}Nd/^{144}Nd)_i$, and major and trace element composition which *Stern et al.* [1984] interpreted as evidence for crustal contamination in the Andean magmas. The Kanuti magmas are also broadly similar to the Oligocene Summer Coon volcanic center [*Zielinski and Lipman*, 1976; *Lipman et al.*, 1978], but the Kanuti rocks have higher-Th and -La contents and a more restricted range of isotopic and major element compositions.

The Yukon River data were collected from several widespread localities, and compositional data indicate that the rocks represent at least three suites: the basalt, rhyolite, and latite at Eagle Slide form one suite; samples 323 and 326 from Poisen Creek form another; and samples 327, 321, and 319 from Poisen Creek form a third. One K/Ar age from each of the groups indicate that the rocks at Eagle Slide may be slightly older (53 Ma) than those form the Poisen Creek area (48–51 Ma). There are insufficient data from a single locality or suite to rigorously model the isotopic and elemental variation within any of the suites. However, the low-MgO contents (<5 wt %) of the basalts indicate that none of them are primary melts of mantle peridotite. Furthermore, initial $^{143}Nd/^{144}Nd$ data (≥0.51266) indicate that none of the rocks are direct partial melts of Paleozoic or older continental crust of the Ruby or Nixon Fork terranes. The basalts probably formed by fractionation of mantle-derived basalts or melting of mafic or ultramafic crustal rocks. Likewise, andesites, dacite, and rhyolite were generated by fractionation of more mafic rocks (perhaps accompanied by assimilation of crustal rocks) or partial melting of the crust. Sample 321 probably formed by mixing between mafic and felsic magmas, but none of the samples that we studied have phenocrysts that would make them likely end-members. The basalt and rhyolite at Eagle Slide have large differences in initial $^{87}Sr/^{86}Sr$ and small differences in initial $^{143}Nd/^{144}Nd$. The trend of the $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$ data from basalt having low initial $^{87}Sr/^{86}Sr$ to rhyolite having high initial $^{87}Sr/^{86}Sr$ (Figure 12) may indicate assimilation during fractionation of a feldspar-dominated assemblage at crustal levels or may indicate that the basalt and rhyolite are unrelated and have two different sources. We modeled partial melting and fractionation-assimilation (AFC) to see if we would distinguish between the two processes in the Eagle Slide rocks. The AFC model used the isotopic composition of the basalt at Eagle Slide to generate the isotopic composition of the rhyolite from the same location (Figure 14). The Yukon River rocks are just inside the southeastern boundary of the Yukon-Koyukuk province, so we tested both oceanic and continental assimilants. The best fit for either assimilant was achieved using high bulk partition coefficients for Sr (3) and Nd (0.5). These D values are reasonable if the fractionating assemblage was dominated by plagioclase and also contained significant amounts of hornblende and/or LREE-enriched accessory minerals. Assimilation of hydrothermally altered oceanic crust was more successfully modeled than assimilation of continental crust (Figure 14, curves 1 and 2), despite using low $^{87}Sr/^{86}Sr$ values for the continental crustal contaminant, although none of the curves have sufficiently low elemental Sr to match the data point for the rhyolite precisely (Figure 14*a*).

Alternatively, the rhyolite may have formed by partial melting of crustal rocks and may have mixed with mantle-derived basalts to produce the latite (sample 334), or even the basalt (sample 332b). We tested this model by calculating batch partial melting models for Rb, Sr, Ba, La, Yb, Th, Sc, Cr, Co, Hf, and K using a number of starting lithologies including average metamorphic rocks, Tozitna terrane, and Koyukuk terrane. None of the partial melting models we calculated were able to produce the extreme LIL-element enrichment and compatible-element depletion of the rhyolite, perhaps indicating that the rhyolite formed by fractionation of more mafic rocks rather than direct partial melting. However, we were able to produce the trace element composition of the latite (sample 334) and basalt (sample 332b) by partial melting of the Angayucham-Tozitna terrane (oceanic crust?) and a mafic tholeiite from the Koyukuk terrane (island arc basalt) (Table 11). The models are constrained mainly by the incompatible elements contents, which require 15–45% or 35–65% melting to form the basalt and 7–22% or 8–30% melting to form the latite from the Koyukuk terrane or Tozitna terrane, respectively. However, the major element composition of the basalt (49.4 wt % SiO_2 and 4.33 wt % MgO) cannot be generated by 45–65% partial melting of another, only slightly more mafic, basalt (47.8 wt % SiO_2 and 6.3 wt % MgO).

In summary, the basalt and rhyolite in the Yukon River area probably did not form by direct partial melting of oceanic or island arc rocks of the Angayucham-Tozitna or Koyukuk terrane, but the latite may have formed this way. The basalts may, however, represent fractionated, mantle-derived melts that assimilated Angayucham-Tozitna terrane or mixed with melts derived from the Angayucham-Tozitna terrane. The rhyolite probably formed by fractionation of more mafic magma accompanied by assimilation of small amounts of crustal rocks having elevated $^{87}Sr/^{86}Sr$. Modeling favors assimilation of seawater-hydrothermally altered oceanic crust rather than Paleozoic or older continental crust. However, we are uncertain if oceanic rocks having elevated $^{87}Sr/^{86}Sr$ exist in the Yukon Koyukuk province as no Sr isotope data greater than 0.7046 are available from the Angayucham-Tozitna terrane. The data indicate that none of the Yukon River volcanic rocks have interacted with large amounts of Paleozoic or older continental crust of the Ruby or Nixon Fork terranes as none of the rocks, including the rhyolite that contains less than 30 ppm Sr, have initial $^{87}Sr/^{86}Sr$ greater than 0.7055 or initial $^{143}Nd/^{144}Nd$ less than 0.51266. However, the Yukon River volcanic rocks may have assimilated small amounts of Paleozoic or older rocks in the form of clasts from marginal conglomerates that rim the Yukon Koyukuk province and are presumed to underlie the volcanic fields. These marginal conglomerates were derived by erosion off the Angayucham-Tozitna and Ruby terranes and may provide a "mixed" assimilant having the appropriate isotopic and elemental composition to generate rhyolite with $(^{87}Sr/^{86}Sr)_i = 0.7050$.

TABLE 11*a*. Partial Melting Model for Tozitna Terrane (Average)

	Rb	Sr	Ba	La	Yb	Th	Sc	Cr	Co	Hf	K × 10^{-2}
C_0	8.5	190	207	10	2.55	1.2	41	113	45.7	2.86	29.885
C_l (334)	50	475	990	32	3.2	5.9	23.9	43.5	25.6	4.6	160.22
C_l (332b)	17	603	543	30	3.9	1.8	24.5	64.4	28.5	4.6	68.90
D	0.1	0.15	0.01	0.01	0.7	0.1	4	5	4	0.5	0.01
F = 0.5	15.5	330.4	409.9	19.8	3.0	2.2	16.4	37.7	18.3	3.8	59.2
F = 0.4	18.5	387.8	509.9	24.6	3.1	2.6	14.6	33.2	16.3	4.1	73.6
F = 0.3	23.0	469.1	674.3	32.6	3.2	3.2	13.2	29.7	14.7	4.4	97.3
F = 0.2	30.4	593.8	995.2	48.1	3.4	4.3	12.1	26.9	13.4	4.8	143.7
F = 0.1	44.7	808.5	1899.1	91.7	3.5	6.3	11.1	24.6	12.4	5.2	274.2
F = 0.05	58.6	987.0	3479.0	168.1	3.6	8.3	10.6	23.5	11.9	5.4	502.3

Equation: $C_l = C_0/[D(1-F)+F]$. C_0, weight concentration of a trace element in the source; C_l, weight concentration of a trace element in the derived melt; D, bulk distribution coefficient of a given trace element for the mineral phases in the source; F, weight fraction of melt relative to original source. Equation from *Schilling and Winchester* [1967]. Partial melting of the Tozitna terrane requires a source having little or no plagioclase (D_{Sr} = 0.15), a small amount of hornblende (D_{Yb} = 0.7 and D_{Hf} = 0.5) and considerable pyroxene and olivine (D_{Cr} = 5, D_{Sc} = 4, D_{Co} = 4).

COMPARISON OF THE FIVE VOLCANIC FIELDS

Rocks from the Sischu and Nowitna fields, which clearly overlie Precambrian and Paleozoic basement (Figure 15), have higher K_2O than rocks from the Blackburn Hills. Samples from the Yukon River field overlap those from the Nowitna field at low-SiO_2 contents but have lower K_2O at SiO_2 greater than 60 wt %. Kanuti samples show a wide range of K_2O contents but appear to be generally lower in K_2O than the Nowitna and Sischu rocks. Most other major and trace elements do not distinguish between within-province rocks from those that occur on the older borderlands. Th contents are similar in the Blackburn Hills, Nowitna, Sischu, and Kanuti rocks and are lower in the Yukon River rocks (Figure 15). La and Ba are higher in the Kanuti and Blackburn Hills group 2 andesites and lower in rocks from the other areas (Figure 15). Sr is highest in the Kanuti field and about the same in rocks from the other areas (Figure 15). Rb contents are highest in the Nowitna, Sischu, and Kanuti samples and are lowest in the Blackburn Hills and Yukon River samples (Figure 15).

Table 12 summarizes compositional data from the five volcanic fields. The volcanic fields erupted through the continental borderlands lack basalt; none of the Late Cretaceous and early Tertiary intrusive or volcanic rocks on the continental borderlands have less than 55 wt % SiO_2. Calc-alkalic rhyolites and dacites from the three fields within the Yukon-Koyukuk province contain phenocrysts of plagioclase, hornblende, biotite, and quartz, whereas rhyolites from the continental borderlands contain plagioclase, sanidine, and quartz and biotite or fayalite. Mildly alkalic rhyolites within the Yukon-Koyukuk province have mineral assemblages and compositions that are typical of oceanic islands that are not underlain by continental crust. Felsic rocks from the Yukon-Koyukuk province have uniformly low initial $^{87}Sr/^{86}Sr$ that contrast sharply with initial $^{87}Sr/^{86}Sr$ values for felsic rocks from the Sischu field (Figure 16). Some of the felsic rocks that intrude or overlie the continental terrane have anomalously high concentrations of U, Th, Sn, W, and F, elements that are indicative of interaction with old continental crust, whereas none of the felsic rocks within the Yukon-Koyukuk province have anomalously high concentrations of these elements (*Moll and Patton* [1983] and Table 13).

Comparison of andesites from the five volcanic fields indicates that the Nowitna volcanic field, which overlies Paleozoic or older continental schist, has isotopic compositions that are grossly similar (initial $^{87}Sr/^{86}Sr$ = 0.70434–0.70509; initial $^{143}Nd/^{144}Nd$ = 0.51256–0.51257) to the Kanuti volcanic rocks and Blackburn Hills group 2 rocks but REE patterns that are like the isotopically more primitive Blackburn HIlls group 1 rocks and the Yukon River area rocks (compare Figures 4, 6, 12, and 13). We interpret the low-HREE contents of rocks from the Kanuti field and group 2 rocks from the Blackburn Hill as indicating formation in a hornblende- or garnet-bearing lower crustal source. Mafic and intermediate rocks from the Nowitna and Yukon River

TABLE 11*b*. Partial Melting Model for Koyukuk Terrane (Tholeiitic Basalt, Sample 84Pa86)

	Rb	Sr	Ba	La	Yb	Th	Sc	Cr	Co	Hf	K × 10^{-2}
C_0	8	550	280	5.24	1.65	0.86	43	110	34	0.91	33.206
C_l (334)	50	475	990	32	3.2	5.9	23.9	43.5	25.6	4.6	160.22
C_l (332b)	17	603	543	30	3.9	1.8	24.5	64.4	28.5	4.6	68.90
D	0.1	0.8	0.01	0.01	0.3	0.05	5	5	3	0.01	0.1
F = 0.5	14.5	611.1	554.5	10.4	2.5	1.6	14.3	36.7	17.0	1.8	60.4
F = 0.4	17.4	625.0	689.7	12.9	2.8	2.0	12.6	32.4	15.5	2.2	72.2
F = 0.3	21.6	639.5	912.1	17.1	3.2	2.6	11.3	28.9	14.2	3.0	89.7
F = 0.2	28.6	654.8	1346.2	25.2	3.8	3.6	10.2	26.2	13.1	4.4	118.6
F = 0.1	42.1	670.7	2568.8	48.1	4.5	5.9	9.3	23.9	12.1	8.4	174.8
F = 0.05	55.2	679.0	4705.9	88.1	4.9	8.8	9.0	22.9	11.7	15.3	229.0

Equation: $C_l = C_0/(D(1-F)+F)$. Partial melting of the Koyukuk terrane requires a source having plagioclase (D_{Sr} = 0.8), pyroxenes, and/or olivine (D_{Sc} = 5, D_{Cr} = 2.7, D_{Co} = 3). All values, except those for distribution coefficients, in ppm.

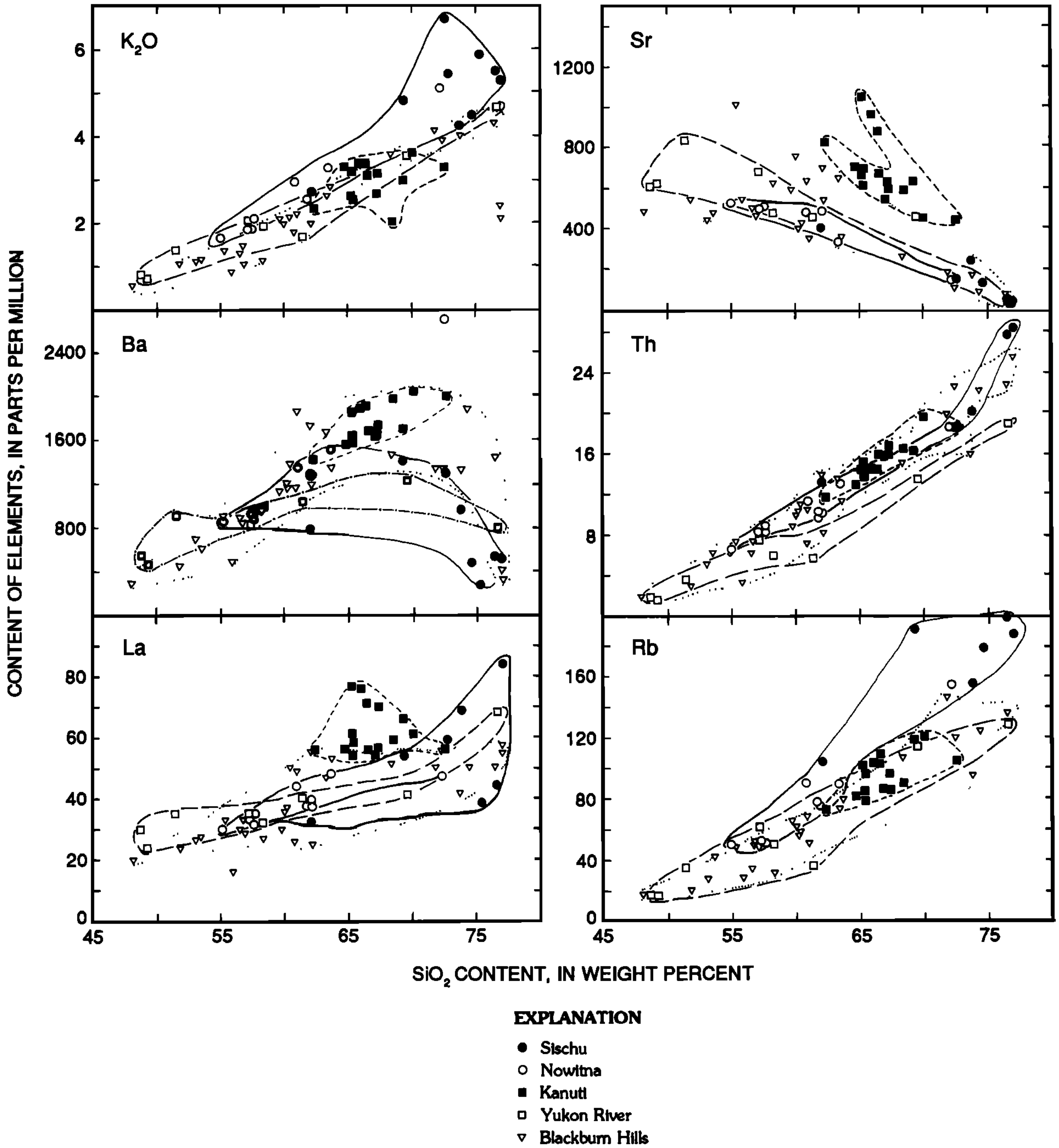


Fig. 15. Comparison of selected elements for all five volcanic fields.

fields and group 1 rocks from the Blackburn Hills have more moderate HREE contents and are interpreted as fractionates of mantle melts that have assimilated crustal material.

Small degrees of isotopic and elemental variation in the Nowitna suite may indicate contamination by Paleozoic or older continental crust. We were initially surprized that the Nowitna rocks did not show stronger evidence for interaction with continental crust. Their moderate isotopic composition may indicate that the isotopic composition of these andesites is not easily modified: $^{87}Sr/^{86}Sr$ does not change easily because the rocks have high-Sr contents (400–500 ppm Sr); $^{143}Nd/^{144}Nd$ is not easily modified if assimilation occurs at crustal levels during plagioclase fractionation. Alternatively, the isotopic composition of the Nowitna magmas may indicate that metamorphic rocks exposed at the surface do not extent to great depths, either because the Ruby and Nixon Fork terranes are thin sheetlike bodies underlain by younger, more mafic crust in the vicinity of the Nowitna field or because a piece of oceanic crust was caught in the boundary between the Ruby and Nixon Fork terranes during terrane accretion.

Isotopic and elemental trends in the Yukon River rocks do not indicate the presence of Paleozoic or older continental crust in the vicinity of the volcanic field and are more indicative of interaction between mantle-derived basalts and the Koyukuk and/or Angayucham/Tozitna terrane. Trends in

TABLE 12. Summary of Compositional Data for the Five Volcanic Fields

	Yukon-Koyukuk Province			Precambrian/Paleozoic Terranes	
	Kanuti	Blackburn Hills	Yukon River	Nowitna	Sischu
Age, Ma	60–56	65–56	53–48	66–63	71–66
Volume, km^3	>1,500	400	>200	2500	>350
Classification	moderate to high-K calc-alkalic	moderate-K calc-alkalic and mildly alkalic	moderate to high-K calc alkalic and mildly alkalic	moderate-K calc-alkalic	shoshonitic to high-K calc-alkalic
Rock types	Chiefly dacite	bas, ande, rhy, grnodrt	bas, ande, dac, rhy, and latite	chiefly ande, minor rhy	chiefly dac+ rhy, minor ande
SiO_2,%	62–72	48–76	48–76	55–64, 72	62–76
Mineralogy	rhy: qtz+olig +hb+mt dac: olig-andes +hb+mt ±opx±cpx	sodic rhy: anorth+Fe-hd CA rhy: plag± bio+hb grnodrt: plag+ortho +bio+hb ande: plag+cpx ±opx±hb+mt bas: plag+cpx +ol+mt	calc-alkalic: dac: plag+qtz+ hb+cpx ande: plag+cpx ±opx±hb mildly alkalic: rhy: plag+anorth +san+qtz; latite: anorth+olig +san+bio+hb; bas: plag+ol +cpx±bio	ande: Plag+cpx±opx+mt rhy: plag+san±bio+mt	rhy: olig+san+qtz +bio+fay Dac: plag+san+qtz +bio+hb ande: plag+bio +mt+hb
Spidergrams	low Nb-Ta	low Nb-Ta, except bas	low Nb-Ta, except bas	low Nb-Ta	highly evolved, generally low Nb-Ta
REE (chondrite normalized)	La = 160–140 Yb = 4–7	two groups of rocks Group 1 La = 60–150, Yb = 10–15 Group 2 La = 80–170, Yb = 4–6 rhy: La = 150–200, Yb = 10–30 grnodrt: La = 150, Yb = 10–20	La = 100 Yb = 10–16	La = 100 Yb = 15	La = 90–800 Yb = 2.5–50
SIR	0.7043–0.7047	Group 1, 0.7027–0.7043 Group 2, 0.7045–0.7052 rhy: 0.7036–0.7050 grnodrt: 0.7039	0.7037–0.7051	0.7043–0.7051	0.7075–0.708
NIR	0.51256–0.51271	Group 1, 0.5129–0.51265 Group 2, 0.51250–0.51269 rhy: 0.51263–0.51292 grnodrt: 0.51273–0.51279	0.51266–0.51280	0.51257	0.51244–0.51252

Abbreviations are as follows: bas, basalt; ande, andesite; rhy, rhyolite; dac, dacite; qtz, quartz; olig, oligoclase; hb, hornblende; mt, magnetite; andes, andesine; opx, orthopyroxene; cpx, clinopyroxene; hd, hedenbergite; anorth, anorthoclase; bio, biotite; CA, calc-alkalic; grnodrt, granodiorite; ol, olivine; san, sanidine; fay, fayalite; SIR, initial $^{87}Sr/^{86}Sr$; NIR, initial $^{143}Nd/^{144}Nd$.

the Blackburn Hills samples suggest that the rocks inherited their isotopic composition from mantle-derived parent magmas or that parent magmas assimilated mafic and intermediate rocks of the Koyukuk terrane at depths greater than the stability field for plagioclase. If the isotopic range of the rocks originated in the mantle, the range may represent mixtures between an asthospheric source and more isotopically evolved continental lithosphere or a mantle source that has been metasomatized by a subduction component contained considerable sediment. The asthospheric mantle is probably an OIB-type mantle source, and its composition may be represented by continental basalts of the Bering Sea province, which have $^{87}Sr/^{86}Sr$ of about 0.7027 and $^{143}Nd/^{144}Nd$ of 0.5130.

The most primitive isotopic composition (lowest initial $^{87}Sr/^{86}Sr$, highest initial $^{143}Nd/^{144}Nd$) from the Blackburn Hills, Nowitna, and Yukon River fields may represent the values closest to those of the parent magmas and ultimately, their mantle source. These values vary with Blackburn Hills basalts having the most primitive values (($^{87}Sr/^{86}Sr)_i$ = 0.7033 and ($^{143}Nd/^{14}Nd)_i$ = 0.51320), Yukon River basalts having slightly more enriched values (($^{87}Sr/^{86}Sr)_i$ = 0.70374 and ($^{143}Nd/^{144}Nd)_i$ = 0.51268) and Nowitna andesites having even more enriched values (($^{87}Sr/^{86}Sr)_i$ = 0.70434 and ($^{143}Nd/^{144}Nd)_i$ = 0.51256).

The Sischu volcanic field is isotopically and elementally evolved and shows the strongest evidence for significant interaction with Paleozoic or older continental crust. None

TABLE 13. Sn, W, U, Th, and F Data on Rhyolites From the Yukon-Koyukuk and Surrounding Metamorphic Borderlands

	Yukon-Koyukuk Province: Blackburn Hills Volcanic Field							
	80ML10c	80ML60d	80ML5c	80ML62a	80ML10e	80ML53c	80ML43a	80ML41d
Sn, ppm	2.3	2.7	2.5	2.7	2.1	2.5	1.7	2.9
W, ppm	2.2	1.1	4.8	1.4	1.9	2.4	1.1	3.4
U, ppm	6.16	6.75	7.51	8.27	6.63	6.55	6.64	9.24
Th, ppm	15.9	22.2	22.5	25.4	17.8	22.3	21.7	22.1
F, wt %	0.02	0.03	0.05	0.02	0.01	0.03	0.02	0.04
	Yukon-Koyukuk Providence: Blackburn Hills Volcanic Field							
	80ML40e	80ML42b	80ML50a	80ML40a	80ML48a	80ML39d	80Pa106a	80Pa106b
Sn, ppm	4.2	4	3.6	1.7	3.3	3.1	1.4	1.9
W, ppm	3.0	3.1	2.7	0.4	2.7	2.3	2.2	2.0
U, ppm	8.67	8.8	8.91	3.77	9.47	7.39	4.69	5.39
Th, ppm	25.4	30.9	22.4	20.1	26.3	19.2	20.2	19
F, wt %	0.01	0.04	0.02	0.01	0.02	0.01	0.02	0.03
	Metamorphic Borderlands: Sischu Volcanic Field					Nowitna Volcanic Field		
	75Pal55	79Pa56a	78Pa36a	77Pa202	77Pa197	78PA78		
Sn, ppm	3	2.4	**17**	3.8	3.2	3.5		
W, ppm	**360**	2.8	**22**	3	2.4	1.8		
U, ppm	6.67	6.49	**26.2**	11.1	4.12	4.51		
Th, ppm	27.6	28.3	**125**	18.5	8.41	18.6		
F, wt %	0.02	0.02	**0.3**	**0.08**	0.06	0.03		

Anomalously high values are highlighted in bold type. Sn by extract heated graphite atomizer-atomic absorption spectrometry; analyst: J. S. Kane [*Aruscavage and Crock*, 1987]. U and Th by delayed neutron counting; analysts: J. Storey, S. Danahey, B. Vaughn, and M. Coughlin [*McKnown and Millard*, 1987]. F analyzed by selected-ion electrode and W analyzed by inductively coupled plasma-atomic emission spectrometry [*Lichte* et al., 1987]; analysts: D. Kobilis. Analytical uncertainties: Sn ± 10%; U ± 5%; Th ± 10%; F ± 5–10%; W ± 10%.

of the felsic rocks from the volcanic fields within the Yukon-Koyukuk province have initial $^{87}Sr/^{86}Sr$ that approaches the initial $^{87}Sr/^{86}Sr$ values of the Sischu volcanic rocks (Figure 16). Some of the felsic rocks from the Sischu volcanic field and felsic plutonic rocks from the surrounding area have high concentrations of U, Sn, W, F, and Th (Table 13), which also suggest that chemically evolved continental crust played a role in their genesis.

Figure 17 shows a cartoon cross section that is a first attempt to interpret the structure of the crust and mantle of the southern border of the Yukon-Koyukuk province based on the chemical and isotopic data of the volcanic rocks. We suggest that most of the asthospheric mantle under the Yukon-Koyukuk province may be chemically similar to the composition of the most primitive Bering Sea basalts, which

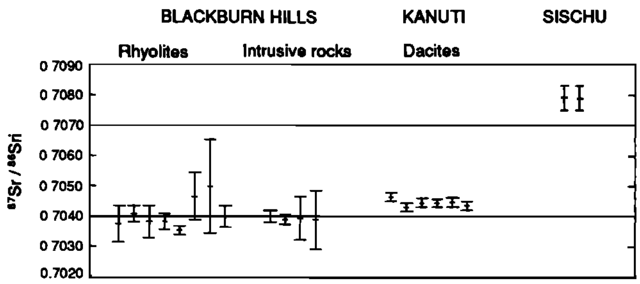


Fig. 16. Summary of initial $^{87}Sr/^{86}Sr$ data for all analyzed rocks having more than 63% SiO_2. Blackburn Hills and Kanuti volcanics have uniformly low initial $^{87}Sr/^{86}Sr$ within total uncertainty. Rocks from the Sischu field have considerably higher initial $^{87}Sr/^{86}Sr$.

have $^{87}Sr/^{86}Sr = 0.7027$ and $^{143}Nd/^{144}Nd = 0.5130$. This mantle may have been metasomatized by a fluid or silicate melt derived from the subducting slab and/or sediments in the Late Cretaceous and early Tertiary. Most of the crust along the southern flank of the Yukon-Koyukuk province is thought to consist of tholeiitic or calc-alkalic island arc rocks which might have moderate isotopic compositions of about $^{87}Sr/^{86}Sr = 0.7040$ and $^{143}Nd/^{144}Nd = 0.5127$, similar to values obtained on early Tertiary intrusive rocks in the province. Small volumes of Early Cretaceous rocks in the Koyukuk terrane are more isotopically evolved, as represented by Yellow River shoshonites (118 Ma) which have $(^{87}Sr/^{86}Sr)_i = 0.7076$ and $^{143}Nd/^{144}Nd = 0.51248$. Some of the magmas in the Yukon River area, which lies near the margin of the Yukon-Koyukuk province, may have interacted with seawater-altered oceanic crust of the Angayucham/Tozitna terrane, which may dip under the volcanic field along the margin of the province and could potentially have $^{87}Sr/^{86}Sr$ as high as 0.7080 and $^{143}Nd/^{144}Nd$ of 0.5132. The Sischu rocks, which probably form by interaction between mantle-derived melts and Paleozoic or older continental crust, are shown overlying continental crust having $^{87}Sr/^{86}Sr = 0.7080–0.738$ and $^{143}Nd/^{144}Nd = 0.51247–0.5118$. The most primitive Nowitna magmas have $^{87}Sr/^{86}Sr = 0.7045$ and $^{143}Nd/^{144}Nd = 0.51257$ and may represent fractionates of parent magmas that formed in Paleozoic lithospheric mantle having that isotopic composition.

Alternatively, the isotopic composition of the continental lithosphere underlying the Nowitna and Sischu fields may be much more evolved; evidence from plutonic rocks to the

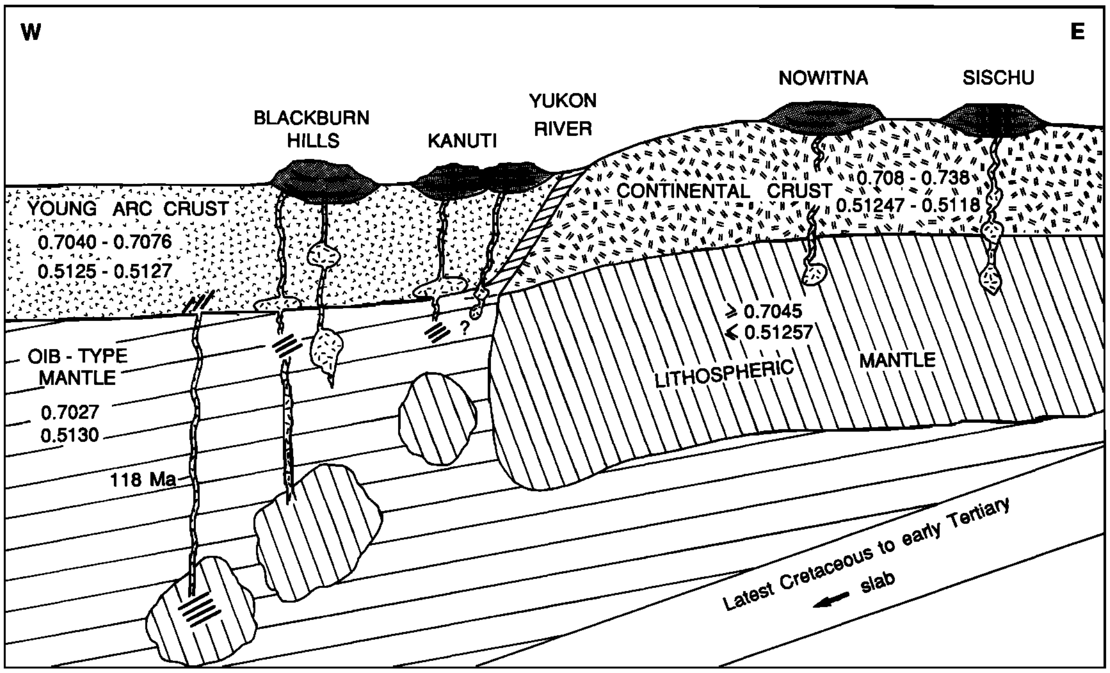


Fig. 17. Cartoon cross section (no scale) depicting proposed model for the isotopic structure of the crust and mantle along the southeast boundary of the Yukon-Koyukuk province and the Ruby, Nixon Fork, and Minchumina terranes in the early Tertiary. The volcanic field discussed in this paper are projected onto an east-west cross section to illustrate their position relative to the margin of the Yukon-Koyukuk province. Sparse gravity data [*Barnes*, 1977] indicate that the present crust in this area is about 30 km thick under both the Yukon-Koyukuk province and the metamorphic terranes. The model proposes that continental lithospheric mantle may have been thrust or "subducted" beneath the Yukon-Koyukuk province during arc-continent collision in the Early Cretaceous, producing a small volume of shoshonitic volcanic rocks having high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$. The figure depicts this underthrust continental lithosphere as large chunks "floating" in asthenospheric mantle, although we can only guess at its configuration in the early Tertiary, 50 m.y. later. Volcanism in the Late Cretaceous and early Tertiary occurred along a new suture to the south. This Late Cretaceous and early Tertiary volcanism, discussed in this paper, is isotopically heterogeneous, and its composition represents contributions from the underlying mantle and crust including the previously underthrust continental lithosphere. See text for further discussion.

north indicates that underthrust continental lithosphere in the westernmost part of the Yukon-Koyukuk province has much higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$. Although the continental lithosphere along the southeastern margin of the Yukon-Koyukuk province may not be the same as that under the western part, the isotopic data on the Late Cretaceous and early Tertiary suites do not constrain the composition of the continental lithosphere very well. The isotopic composition of Nowitna parent magmas could represent well-mixed contributions from both asthospheric and highly evolved continental lithospheric sources.

Variation within the Nowitna suite from andesite to high-silica andesite may represent assimilation of Paleozoic or older continental crust. The one sample from the Blackburn Hills that plots in the low $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ field may represent mixing between the mantle-derived magmas and Paleozoic or older lower continental crust, which would have retarded $^{87}Sr/^{86}Sr$ relative to $^{143}Nd/^{144}Nd$.

DOES CONTINENTAL CRUST UNDERLIE THE YUKON-KOYUKUK PROVINCE?

At face value the Sr and Nd isotopic compositions of the five Late Cretaceous and early Tertiary volcanic fields indicate that continental crust of the Ruby and Nixon Fork terranes does not appear to underlie the southeastern part of the Yukon-Koyukuk province. If felsic, highly enriched continental crust underlies the Yukon-Koyukuk province, we would expect its composition to be reflected in the composition of the volcanic rocks, especially the felsic rocks, most of which have initial $^{87}Sr/^{86}Sr$ less than 0.7045 and initial $^{143}Nd/^{144}Nd$ greater than 0.5125. However, many of the more mafic andesites and dacites in the Yukon-Koyukuk province have initial $^{87}Sr/^{86}Sr$ as high as 0.7052. These magmas, which are represented by the Kanuti volcanic rocks and the group 2 rocks from the Blackburn Hills, are interpreted as lower crustal melts of the underlying island arc Koyukuk terrane and plot within the range of evolved island arcs having no continental underpinnings (Figure 6). The Early Cretaceous Koyukuk terrane consists of a compositionally varied island arc assemblage, ranging from arc tholeiitic to calc-alkalic to shoshonitic. Very few isotopic data are available for most of this terrane, and we initially expected it to have typical island arc $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values, as 90% of arc lavas have $^{87}Sr/^{86}Sr$ = 0.7032–0.7045 and $^{143}Nd/^{144}Nd$ = 0.5128–0.5131 [*Morris and Hart*, 1983]. However, shoshonites from the Koyukuk terrane in the Yellow River area have much higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ (initial $^{87}Sr/^{86}Sr$ = 0.7076 and measured $^{143}Nd/^{144}Nd$ = 0.5125 (S. Bergman, personal communication, 1986)) than typical island arcs. The $^{87}Sr/^{86}Sr$ composition of the shoshonites may reflect interaction with Cretaceous seawater, but the low measured $^{143}Nd/^{144}Nd$ and high-LIL element contents of these rocks probably indicate the presence of more isotopically enriched material being subducted beneath the arc at this time. Later, in the early Tertiary, lower crustal roots of the Early Cretaceous arc, including some shoshonitic rocks, may have partially melted to form the Kanuti and Blackburn Hills group 2 rocks. This model succeeds only in removing the problem of the source of the high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ component one step, however, away from the early Tertiary and into the Early Cretaceous. The ultimate question remains: What is the source of the high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ component in the Yukon-Koyukuk province? We suggest that the ultimate source of the high $^{87}Sr/^{86}Sr$–low $^{143}Nd/^{144}Nd$ component is probably continental lithospheric mantle, which may have been thrust or "subducted" under the Yukon-Koyukuk province during arc-continent collision in the Early Cretaceous. In this model most of the brittle crust would be scraped off and obducted, forming the Ruby terrane, whereas the more ductile lithospheric mantle (and possibly slivers of the crust) would be subducted. The subducted continental lithosphere would be the source of the shoshonites erupted at 118 Ma. The Sr and Nd isotopic compositions of the shoshonites are even more evolved than the most evolved early Tertiary rocks in this part of the Yukon-Koyukuk province, perhaps indicating that the most isotopically evolved material (crust?) that was "subducted" in the Early Cretaceous melted entirely to produce the shoshonites and no longer occurs beneath the province. The isotopic composition of the most enriched rocks in the Kanuti and Blackburn Hills fields is the same as the isotopic composition of the Nowitna volcanic rocks, which formed in an area underlain by old continental lithosphere. This may indicate that early Paleozoic lithospheric mantle may still extend under parts of the Yukon-Koyukuk province. The Paleozoic or older continental lithosphere may have been the source of the shoshonites in the Early Cretaceous, and the lower crustal roots of these shoshonites may be part of the source of the Kanuti and Blackburn Hills group 2 rocks in the early Tertiary.

APPENDIX

Analytical Procedures

Major elements and the trace elements Ba, Rb, Sr, Zr, Y, and Nb were measured by wavelength dispersive X ray fluorescence at the U.S. Geological Survey (USGS) in Denver. Other trace elements were analyzed by instrumental neutron activation at the USGS facilities in Reston. Uncertainties for the major elements are 2%; uncertainties for trace elements are less than 5%, except for analyses of Gd, Tb, and Tm which have precision no better than 10% due to spectral interference.

Samples for isotopic analyses were prepared as follows: Between 0.3 and 0.5 g of whole rock powder were dissolved in HF and $HClO_4$ acids. Rb, Sr, and the REE were separated using standard cation exchange techniques with 3 *N* and 6 *N* HCl as eluants. Nd was extracted from the REE concentrate utilizing 2-methyllactic acid. Several samples having high CO_2 were treated with 1 *N* HCl to dissolve excess carbonate, which was then decanted off before the rest of the sample was dissolved in HF and $HClO_4$. Duplicates of the HCl-treated samples that were not treated with HCl gave identical values to the treated samples within analytical uncertainty (Table 5).

Sr isotopic compositions were measured on a National Bureau of Standards (NBS) 6 inch mass spectrometer. No Sr data were collected if ^{85}Rb was present. Measured $^{87}Sr/^{86}Sr$ were normalized to an $^{87}Sr/^{86}Sr$ ratio of 0.11940. Four analyses of NBS SRM 987 Sr standard give an average value of 0.71020 and range from 0.71016 to 0.71023. One analysis of BCR-1 gave a value of 0.70487.

Nd isotopic compositions were measured on a Finnigan-Mat 261 thermal ionization mass spectrometer, utilizing dynamic double collection of two isotopes and fully automatic operation. Sm was monitored at mass 147, and Nd data were not collected unless Sm was negligible. Measured $^{143}Nd/^{144}Nd$ ratios were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.72190. Analyses of a laboratory Nd standard of Johnson-Mathey Nd metal run during the time period that these samples were analyzed gave a mean of 0.51171 ± 0.000014 and a range of 0.51169–0.51172. BCR-1 gives a value of 0.51263; in the range observed by other laboratories.

Uncertainties in initial isotopic ratios were propagated to include uncertainties in elemental concentration measurements, isotopic ratio measurement, and reported age and are reported at the 95% confidence level. These uncertainties are much larger in some cases than those for only the mass spectrometer runs, but they provide a more realistic estimate for the purpose of comparing initial ratios from a variety of rock samples. Precision of mass spectrometry on individual samples are reported at the 67% confidence level.

Nomenclature

Nomenclature used in this report is as follows: Basalt has less than 53% SiO_2, andesite has 53–63% SiO_2, dacite has 63–70% SiO_2, and rhyolite has more than 70% SiO_2. Andesites were designated as high, moderate, and low K by the criteria of *Gill* [1981]. The term shoshonite is used to describe rocks that have $K_2O > Na_2O$ and K_2O greater that high-K calc-alkalic rocks but retain other characteristics of the calc-alkalic suite such as high Al and low Ti, Nb, and Ta and lack iron enrichment [*Morrison*, 1980]. Another word for these rocks would be "arclike alkalic rocks" as described in the recent section of the *Journal of Geophysical Research* edited by S. Box and M. Flower. Plutonic rocks are classified on the basis of modal mineralogy after *Streikeisen* [1976]. All samples are recalculated on a 100% anhydrous basis before plotting or classification.

Rock Alteration

Most of the rocks are moderately altered. Rocks from the Kanuti volcanic field and the Yukon River area average less than 1.5% H_2O^t and 0.03% CO_2; those from the Nowitna field have 0.94–1.6% H_2O^t and 0.01–0.63% CO_2. In the Blackburn Hills the volcanic rocks are generally more altered (andesites: 1–4% H_2O^t and 0.02–1.1% CO_2; rhyolites: up to 6% H_2O^t and up to 0.5% CO_2) than the plutonic rocks (0.5–1.2% H_2O; less than 0.15% CO_2). Almost all the andesites and basalts that we analyzed from the Nowitna, Blackburn Hills, and Yukon River areas contain fresh plagioclase and pyroxene phenocrysts which suggests that most of the alteration is concentrated in the groundmasses. The Kanuti volcanic rocks also have fresh plagioclase and pyroxene, but hornblende and biotite vary from fresh to rimmed by iron oxides to replaced by iron oxides. The groundmass of most samples is fresh looking except for one sample which has patches of zeolites. The Sischu volcanic field has the most altered rocks of all the volcanic fields we studied. Rocks have 0.75–2.75% H_2O and 0.05–1.6 % CO_2. Mafic minerals are often altered beyond recognition.

Hydrothermal alteration has the potential of disturbing the Rb and Sr contents of the rocks, thereby altering the $^{87}Sr/^{86}Sr$ and/or the Rb/Sr ratio of the rocks. Furthermore, alteration of Rb/Sr ratios can result in miscalculation of Sr initial ratios if the time interval between emplacement and alteration is large [*Criss and Fleck*, 1987]. However, the rocks described in this study probably did not undergo significant alteration of initial $^{87}Sr/^{86}Sr$ because nonmarine hydrothermal fluids would be expected to contain very little dissolved Sr and the small amount of Sr in the water would be derived from the rocks themselves, not from an external reservoir having a markedly different Sr isotopic composition [*Criss and Fleck*, 1987]. Furthermore, most of the rocks have fairly high-Sr contents, and their Sr isotopic composition would not be easily altered. The exception is the low-Sr rhyolites (<50 ppm) which may have altered initial $^{87}Sr/^{86}Sr$. Alteration of $^{87}Sr/^{86}Sr$ is more likely in oceanic environments because seawater contains significant Sr having a $^{87}Sr/^{86}Sr$ ratio of 0.7080. Studies on the northern Idaho Batholith showed that hydrothermal alteration systems did not profoundly influence the Sr isotope ratios of the plutonic rocks, despite evidence for major ∂O^{18} depletions [*Criss and Fleck*, 1987].

Petrographic Descriptions of Analyzed Samples

Nowitna volcanic field. Sample 75CH67: Andesite having 1% phenocrysts of altered olivine in a holocrystalline groundmass of fine-grained plagioclase, clinopyroxene, magnetite, and ilmenite. Sparse glomeroporphyritic clots.

Sample 81ML1: Andesite having 20% phenocrysts of plagioclase, clinopyroxene, and orthopyroxene in a holocrystalline intergranular groundmass of plagioclase, pyroxene, and magnetite. Abundant glomeroporphyritic clots.

Sample 81ML2: Andesite having 10% fine-grained phenocrysts of plagioclase (An_{70}-An_{38}) clinopyroxene and orthopyroxene (En_{82}-En_{65}) in a pilotaxitic groundmass of plagioclase, pyroxene, and magnetite. Trace apatite. Most plagioclase phenocrysts are clear and inclusion-free, but some have abundant glass inclusions in their cores.

Sample 81ML3: Andesite having 7% medium-grained phenocrysts of oscillatory-zoned plagioclase, clinopyroxene, and orthopyroxene in a groundmass of felted plagioclase, very fine-grained granular pyroxene, and opaque oxides. Trace apatite.

Sample 81ML5: High-silica andesite having 1% fine-grained phenocrysts of plagioclase, clinopyroxene and magnetite in a groundmass of very dark glass filled with black opaque dust.

Sischu volcanic field. Sample 79Pa12: High-silica andesite having 30% phenocrysts of plagioclase, 10% phenocrysts of hornblende or pyroxene replaced by biotite, and 1–2% magnetite phenocrysts. Groundmass of felted feldspars and very fine-grained opaque oxides.

Sample 78Pa36: Rhyolite having 20% coarse-grained phenocrysts of chiefly sanidine (some with oligoclase in their cores) and quartz. Tiny crystals of fayalite. Groundmass of polycrystalline quartz and feldspar and 1–2% opaque oxides.

Sample 79Pa56: Rhyolite having 10% medium-grained phenocrysts of oligoclase (An_{23}-An_{29}), sanidine, and quartz. Sparse microphenocrysts of opaque oxides and altered mafic minerals (hornblende, pyroxene or biotite?). Groundmass of partially devitrified glass. Trace apatite.

Sample 75Pa155: Rhyolite having 10% medium-grained phenocrysts of oligoclase, quartz, and sanidine in a groundmass of very fine grained devitrified glass. Trace zircon and apatite.

Sample 75Pa156: Dacite having phenocrysts of andesine (An_{34}-An_{46}) and a trace sanidine in a groundmass of devitrified glass.

Yukon River area. Sample 81Pa332b: Basalt having 20–25% coarse-grained phenocrysts of chiefly labradorite to andesine (An_{68}-An_{34}) and sparse olivine (Fo_{85}-Fo_{55}) in a groundmass of plagioclase laths, magnetite, ilmenite, and very fine grained granular pyroxene and sparse biotite and amphibole.

Sample 81Pa334: Latite having two populations of plagioclase phenocrysts: One with strongly absorbed cores, dark with inclusions, and thin clear rims: the other having clear cores surrounded by dark inclusion-filled mantles. Groundmass chiefly clear fine-grained plagioclase laths, opaque oxides, and brown glass. Some blobs in the groundmass (inclusions?) are rich in plagioclase and clinopyroxene.

Sample 81Pa330: Rhyolite having 10% medium-grained phenocrysts of anorthoclase, quartz, and sanidine. Groundmass of partially devitrified spherulitic glass, sparse biotite, and magnetite.

Sample 81Pa327: Basalt having very sparse phenocrysts of olivine, in a groundmass of abundant plagioclase laths fine-grained granular pyroxene and opaque oxides.

Sample 81Pa321: Andesite having 10% phenocrysts of coarse-grained quartz and plagioclase. Plagioclase crystals have clear cores surrounded by thick sieve-textured mantles, both of which are oligoclase (An_{28}-An_{22}), surrounded by clear rims of more calcic andesine to labradorite (An_{69}-An_{44}). Sparse olivine(?) phenocrysts replaced by greenish-brown alteration. Groundmass of plagioclase laths, granular pyroxene, and opaque oxides. Sparse green equant alteration minerals (after olivine? or hornblende?) also occur in the groundmass.

Sample 81Pa326: Basalt having 10% medium-grained phenocrysts of plagioclase and a reddish-brown alteration mineral (after hornblende?) in a holocrystalline groundmass of plagioclase, tiny clinopyroxene, and magnetite.

Sample 81Pa323: Andesite having 5% fine-grained phenocrysts of oscillatory zoned labradorite (An_{75}-An_{49}), orthopyroxene, and clinopyroxene in a holocrystalline pilotaxitic/intergranular groundmass of plagioclase laths, granular pyroxene, ilmenite, and magnetite.

Sample 81Pa319: Dacite having 25% phenocrysts of plagioclase, hornblende, biotite, and magnetite in a groundmass of devitrified glass and sparse opaque oxides. Some prehnite in vugs.

Kanuti volcanic field. Sample 81ML300: Dacite having 4% phenocrysts of chiefly oscillatory zoned plagioclase and pale yellow to green hornblende. Sparse phenocrysts of orthopyroxene. Microphenocrysts of plagioclase, orthopyroxene, clinopyroxene, and magnetite in a groundmass of devitrified glass. Hornblende phenocrysts have dark oxide rims. One xenolith of schist consists of sillimanite, albite, and dark green spinel.

Sample 81ML303: Dacite having 2% phenocrysts of clinopyroxene, orthopyroxene, and sparse magnetite in a groundmass of plagioclase microlites, opaque oxides, and devitrified glass. Rock contains one xenocrysts of andalusite.

Sample 81ML307: Dacite having 25% phenocrysts of oscillatory zoned plagioclase, hornblende, and magnetite in a groundmass of very fine grained felted plagioclase and pale devitrified glass.

Sample 81ML311: Dacite having 10% phenocrysts of quartz, plagioclase (zoned oligoclase to andesine), biotite, hornblende, and clinopyroxene in a groundmass of felted fine-grained plagioclase microlites, opaque oxides, and devitrified glass.

Sample 81ML314: Dacite having 3% phenocrysts of clinopyroxene, orthopyroxene, oscillatory zoned labradorite (An_{64}-An_{45}), and magnetite. Glomeroporphyritic clots of pyroxene are common. Groundmass of felted plagioclase laths.

Sample 81ML319: Dacite having 25% phenocrysts of oscillatory zoned plagioclase, brown hornblende, and minor magnetite in a groundmass of euhedral plagioclase and opaque oxides in colorless glass.

Sample 81Pa400a: Rhyolite having 3% phenocrysts of plagioclase, opaque oxides, and sparse brown hornblende and clinopyroxene. Abundant oxides replacing altered mafic minerals. Microphenocrysts of plagioclase and opaque minerals in patchy devitrified glass.

Sample 81Pa400b: Rhyolite having 25% phenocrysts of plagioclase, quartz, biotite, and opaque minerals in a groundmass of plagioclase microlites, opaque minerals, and devitrified glass. Some patches of zeolites. Trace of apatite and possible allanite.

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