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# Chapter 25

# *Isotopic composition of the igneous rocks of Alaska*

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## INTRODUCTION

The isotopic-tracer data that are currently available on the igneous rocks of Alaska are inadequate to fully characterize the enormous areas of magmatic rock that are exposed on this subcontinent. Nevertheless, the existing data are quite useful for interpreting the origin and evolution of individual magmatic suites and their related ore deposits, the details of crustal growth in island arcs, the genesis of major continental-margin batholiths, and the nature of basement underlying vast areas of the remote interior.

This chapter is a summary of isotopic-tracer data on Mesozoic and Cenozoic igneous rocks of Alaska. Data published prior to the manuscript deadline of December 1986 are included, as are new data collected by the author from 1977 to 1986 in the course of collaborative studies with U.S. Geological Survey colleagues (references are provided if published prior to printing of this volume). The magmatic rocks are discussed in four sections: Mesozoic volcanic provinces, major Mesozoic to Cenozoic batholiths, magmatic suites of economic interest, and igneous rocks in Alaskan tectonostratigraphic terranes. Some of the longer subsections are followed by a one-paragraph summary that attempts a brief, generalized interpretation of the various isotopic results. The final section summarizes the Sr isotope data on a map of Alaska, and discusses the inferred nature of the deep continental crust.

Throughout the text, acronyms are used in place of the more cumbersome isotopic ratios, as follows:

Initial $^{87}Sr/^{86}Sr$ ratio(s) = SIR
Initial $^{143}Nd/^{144}Nd$ ratio(s) = NIR
Initial $^{176}Hf/^{177}Hf$ ratio(s) = HIR
Initial $^{206}Pb/^{204}Pb$ ratio(s) = PIR6
Initial $^{207}Pb/^{204}Pb$ ratio(s) = PIR7
Initial $^{208}Pb/^{204}Pb$ ratio(s) = PIR8

Locations of geologic, geographic/physiographic, and tectonostratigraphic features referred to in this chapter are shown respectively on Plate 1 (Beikman), Plate 2 (Wahrhaftig), and Plate 3 (Silberling and others) of this volume.

## CENOZOIC VOLCANIC PROVINCES

### *The Aleutian magmatic province*

Most of the published isotopic results in Alaska are on samples from the Aleutian Islands. The primary topic of interest has been the generation of island-arc magmas in an arc that is built on oceanic crust west of, and continental crust east of, the edge of the Bering Sea shelf. Various investigators have used isotope ratios to help evaluate the relative contribution of the many possible sources of arc magmas. These sources include rocks entrained on the subducted slab (ocean-ridge rocks, seamounts, pelagic and terrigenous deposits), the upper mantle overlying the slab, and the crust below the active volcanoes. A clearly written summary of the isotopic aspects of magmas erupted in arcs, including several examples from the Aleutians, is given by Hawkesworth (1982).

The earliest major study of Pb and Sr isotopes in Aleutian volcanic rocks was made by Kay and others (1978), who analyzed samples from nine volcanoes located both east and west of the edge of the Bering Sea shelf. The observed ratios do not vary along the strike of the arc (Table 1), suggesting that continental crust under the eastern part of the arc did not contribute significantly to the magmas. SIR of 0.7028 to 0.7037 are among the lowest observed in island arcs. PIR7 are intermediate between those of oceanic basalt and continent-derived sediment. Kay and Kay (this volume) proposed a source of arc magma that contained about 2 percent by mass of subducted sediment. The remaining melt could be derived from the subducted oceanic crust and the overlying mantle. In a related study, Kay (1978) described uncommon Aleutian magnesian andesites having distinct isotopic character and chemistry suggestive of an origin by equilibration of hydrous melt rich in large-ion-lithophile (LIL) elements from subducted oceanic basalt with LIL-element-poor mantle overlying the subduction zone.

The zoned Captains Bay pluton of gabbro to granite on Unalaska Island (eastern Aleutians) was studied by Perfit and Lawrence (1979) and Perfit and others (1980). They found SIR in the range 0.7030 to 0.7038, similar to that of Aleutian volcanic rocks. Delta $^{18}O$ values for whole-rock samples are –1.0 to 7.0

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TABLE 1. ISOTOPIC RANGES FOR CENOZOIC VOLCANIC ROCKS OF ALASKA

| Location | SIR* | NIR† | PIR6 | PIR7 | PIR8 | HIR | References§ |
|---|---|---|---|---|---|---|---|
| **Aleutian Islands and Alaska Peninsula** | | | | | | | |
| All except magnesian andesites | 0.70284–0.70369 | 0.51295–0.51309 | 18.701–18.916 | 15.515–15.602 | 38.127–38.513 | 0.28317–0.28326 | 1, 3–11 |
| Magnesian andesites | 0.7027 –0.70285 | | 17.856–18.359 | 15.416–15.471 | 37.313–37.815 | | 2 |
| **Bering Sea** | | | | | | | |
| Abyssal plain tholeiite | 0.70278 | 0.51316 | | | | | 1, 11 |
| Nunivak Island | 0.70251–0.70330 | 0.51289–0.51315 | 18.628 | 15.457 | 38.112 | | 12–16 |
| Pribilof Islands | 0.70274–0.70293 | 0.51303–0.51308 | 18.806–19.042 | 15.476–15.494 | 38.274–38.483 | | 1, 11 |
| Saint Lawrence Island | 0.70340–0.70374 | 0.51285–0.51288 | | | | | 11 |
| **Gulf of Alaska area** | | | | | | | |
| Kodiak and Hodgkins seamounts | 0.70397 | | 19.12–19.34 | 15.53–15.55 | 38.45–38.63 | | 1 |
| Mount Edgecumbe volcanic field | 0.70291–0.70410 | | 18.48–19.16 | 15.56–15.68 | 38.17–38.85 | | 17–20 |
| **Mainland Alaska volcanic fields** | | | | | | | |
| Blackburn Hills | 0.7033–0.7052 | 0.51253–0.51290 | | | | | 21 |
| Kanuti | 0.7043–0.7048 | 0.51248–0.51267 | | | | | 21 |
| Nowitna | 0.7043–0.7051 | 0.51256–0.51257 | | | | | 21 |
| Sischu | 0.7075–0.7079 | 0.51244–0.51247 | | | | | 21 |
| Yukon River | 0.7037–0.7051 | 0.51266–0.51280 | | | | | 21 |

*All ratios normalized to $^{86}Sr/^{88}Sr = 0.11940$

†All ratios normalized to $^{146}Nd/^{144}Nd = 0.72190$

§1. Kay and others, 1978; 2. Kay, 1978; 3. Perfit and Lawrence, 1979; 4. Perfit and others, 1980; 5. McCulloch and Perfit, 1981; 6. Morris and Hart, 1983; 7. White and Patchett, 1984; 8. Myers and others, 1985; 9. Perfit and Kay, 1986; 10. Morris and Hart, 1986; 11. von Drach and others, 1986; 12. Mark, 1972; 13. Zartman and Tera, 1973; 14. Menzies and Murthy, 1980a; 15. Menzies and Murthy, 1980b; 16. Roden and others, 1984; 17. Myers and Marsh, 1981; 18. Kosco, 1981; 19. Myers and others, 1984; 20. Myers and Sinha, 1985; 21. Moll-Stalcup and Arth, 1989.

per mil. The lowest values, found in the intermediate rocks, reflect interaction of the pluton with large volumes of low-$\delta^{18}O$ meteoric water. No correlation of SIR and $\delta^{18}O$ was found; Sr was apparently unaffected by the exchange. Perfit and coworkers proposed that the intermediate rocks were the result of fractional crystallization of high-Al basaltic magma at crustal levels under conditions of increasing water fugacity. They suggested that aplitic granites crystallized from a late-stage, volatile-rich liquid.

A Nd and Sr isotopic study by McCulloch and Perfit (1981) included volcanic samples from islands farther to the west than the earlier studies discussed above, as well as two plutonic samples from Unalaska. SIR for volcanic and plutonic rocks were in the narrow range of 0.7029 to 0.7034. Combined Nd and Sr data led McCulloch and Perfit to suggest that 2 to 8 percent of ocean sediment was added to seawater-altered oceanic igneous crust to produce magmas related to the subducted slab. They suggested that the overlying mantle wedge may react with the slab-related magmas, but that overlying continental crust, if present, made little or no contribution to the magmas.

Morris and Hart (1983) compared SIR, NIR, and PIR between Cold Bay volcanics on the main Aleutian volcanic front near the tip of the Alaska Peninsula, and Amak Island volcanics located about 50 km behind the front. Both suites fell within the previously reported ranges, but Morris and Hart noted small secular increases in SIR and PIR at Cold Bay, which they correlated with increasing $SiO_2$ and decreasing CaO contents. For magmatic arcs in general, they noted the similarity of SIR and NIR values to those of ocean islands and suggested that the sources were the same. They thus favored derivation of Cold Bay and Amak suites by melting of a hybrid "plum-pudding" or metasomatically veined mantle composed of pieces of the lower mantle (of the type that yields some ocean-island basalts) intermixed with depleted upper mantle (of the type that is the source for normal ocean-ridge basalts). A discussion of the conflict between this and earlier models is given by Perfit and Kay (1986) and Morris and Hart (1986).

White and Patchett (1984) examined the isotopic ratios of Hf, Nd, and Sr in samples from a variety of arcs, including the Aleutians at Little Sitkin. They showed that HIR in island-arc magmas correlate positively with NIR and negatively with SIR. The HIR for several arcs, including the Aleutians, overlap the HIR of normal ocean-ridge basalts, but the HIR for other arcs have lower values. Of the arcs examined, the Aleutians have the lowest SIR, highest NIR, and highest HIR, and are closer in these values to ocean-ridge basalts than any other arc suite. White and Patchett acknowledge the similarity of the isotopic ratios for arc magmas to those of ocean-island magmas as noted by Morris and Hart (1983), but suggest that the mantle wedge above subduction zones is chemically like that beneath ocean ridges. They ascribed some of the isotopic differences between ridge basalts and island-arc magmas like those of the Aleutians to incorporation of 1 to 2 percent of subducted continent-derived or pelagic sediment in the sources.

Myers and others (1985) studied SIR and other chemical features of Adak and Atka lavas in order to compare a small, presumably immature volcanic center (Adak) with a larger, presumably more mature one (Atka). Although all data fell in the previously reported range of SIR, lavas at Adak are more variable in SIR and have a lower average value than those at Atka. The variability was ascribed to contamination of lavas by interaction with nonradiogenic ultramafic wall rock, in a "dirty plumbing system." Similar contamination would not occur in a "mature" edifice such as Atka where there is a "clean plumbing system" that provides lavas of more uniform isotopic composition.

Von Drach and others (1986) provided additional geographic coverage for Nd and Sr isotopic data. They noted the narrow range of NIR and larger spread of SIR in all Aleutian magmas, and reemphasized the role of seawater alteration because it has no substantial effect on NIR, but can influence SIR. After compiling average trace-element contents and isotopic ratios for arc volcanics and potential source materials, they estimated that Aleutian magmas are melts from mixtures of seawater-altered ocean-ridge basalt and about 4 percent of pelagic sediments.

Brown and others (1982) and Tera and others (1986) provided independent evidence for incorporation of sediments in Aleutian magma sources by measuring $^{10}Be$ contents in several Aleutian volcanic samples. $^{10}Be$ is formed in the atmosphere by reaction of oxygen and nitrogen with cosmic rays. It reaches the Earth's surface via precipitation and is incorporated into sediments and soils. Because $^{10}Be$ has a short half-life (1.5 m.y.), only magmas that include recently formed sediments in their source will show its presence. Sediments must be formed, subducted, and melted in less than about 10 m.y. Of 12 arcs that these authors measured, only the Aleutians and two others showed significant levels of $^{10}Be$. Aleutian basalts and andesites range from 2.0 to $15.3 \times 10^6$ and average $4.1 \times 10^6$ atoms of $^{10}Be$ per gram of sample. These values compare with $^{10}Be$ concentrations of less than $1 \times 10^6$ atoms per gram (values indistinguishable from 0 at current analytical sensitivity) in lavas from ocean-ridge basalts, ocean islands, or flood basalts. Rocks from Bogoslof have the highest values (5.2 and $15.3 \times 10^6$), but otherwise, there is no geographic trend or polarity within the arc. Although Brown, Tera, and others find it a reasonable hypothesis to suggest that the $^{10}Be$ reflects incorporation of Miocene or younger sediments in the magma source, they note that two samples from Cold Bay that contain $^{10}Be$ do not have a sedimentary signature for Pb isotopes. Most workers rule out contamination by surface sources of $^{10}Be$, as might occur during hydrothermal alteration, etc. The measured $^{10}Be$ levels are low enough, however, that they would be strongly influenced by contamination if it did occur.

*Aleutian summary:* Most isotopic studies indicate that the Aleutian-arc mafic magmas have a source composed of seawater-altered ocean-floor basalt combined with a few percent of sediment. Some interaction of subduction-produced magma with overlying mantle is probable. Interaction of magma with overlying continental crust, where present, is not required by the iso-

topic data, but cannot be precluded because the isotopic character of the crust is not much different from that of the Aleutian magmas (see section of this chapter on Peninsular terrane). Intermediate to silicic magmas appear to result primarily by fractional crystallization of mafic magmas. Evolution of highly evolved magmas may involve volatile-rich fluid.

### *Bering Sea magmatic rocks*

The area north of the Aleutians includes the Bering Sea abyssal plain to the west and the Bering Sea shelf to the east. Igneous rocks have been isotopically studied primarily because they might reflect the nature of sources in a back-arc basin. Analyses are of samples from Deep Sea Drilling Project (DSDP) site 191 on the western side of the abyssal plain in the Kamchatka Basin; from the Pribilof Islands of St. George and St. Paul toward the edge of the Bering Sea Shelf and, respectively, about 350 and 425 km from the arc; and from Nunivak Island and St. Lawrence Island on the Bering Sea Shelf, respectively, about 550 and 950 km from the arc.

The abyssal plain tholeiite from DSDP site 191 showed NIR and SIR (Table 1) that are typical of ocean-ridge basalts (Kay and others, 1978; von Drach and others, 1986). Because only one site has been analyzed from the abyssal plain, no geographic variations on the plain are known.

The Pribilof Islands were examined by Kay and others (1978) for SIR and PIR, and by von Drach and others (1986) for SIR and NIR. Compared with Pacific ocean-ridge basalts, the Pribilof rocks have higher PIR6. Compared with Aleutian magmas they have lower PIR7 and generally lower SIR and higher NIR. All the ratios fall within the broad field of ocean-island basalts.

Samples from Nunivak Island were studied by Zartman and Tera (1973), who measured PIR on an inclusion of peridotite in basinite and on an alkali basalt sample. The PIR6, PIR7, and PIR8 are distinct for each sample, leading Zartman and Tera to suggest that the peridotite and basalt were not cogenetic. They noted that all ratios fall in the range of abyssal tholeiites and alkali-island basalts.

Mark (1972) measured SIR in young (<6 m.y.) basalt lavas on Nunivak Island and found a range of 0.7025 to 0.7033. The minor volume (≈2 percent) of basanites had a mean SIR of 0.7027, whereas the more abundant tholeiites and alkali olivine basalts had a mean of 0.7031. Menzies and Murthy (1980a, b) reported NIR for these rocks of 0.51289 to 0.51304, and noted no correlation with chemistry or SIR. They also studied mantle inclusions of pargasite-lherzolite and kaersutite megacrysts and found the same range of SIR and NIR as in the lavas. However, pargasite, diopside, and mica in nodules have NIR near 0.51302, whereas kaersutite has NIR of 0.51281. Menzies and Murthy suggeted that recent (<200 m.y.) metasomatic event(s) produced an inhomogeneous mantle having parts that are "veined" by kaersutite, and parts that contain pargasite and mica. Melting of varying proportions of these components would produce the observed isotopic heterogeneity of the Nunivak lavas. They also noted the similarity of Nunivak values for SIR and NIR to those of ocean-island basalts. One sample measured by von Drach and others (1986) fell in the same field. Roden and others (1984) added SIR and NIR data for additional peridotite and pyroxenite inclusions at Nunivak, and also suggested that the mantle had been recently metasomatized. They proposed, however, that the peridotites were pieces of wall rock that had been infiltrated by a silicate melt or volatile-rich fluid derived from a parental magma, that this magma was probably related to the Nunivak volcanism, and that crystal segregations from it formed the pyroxenite inclusions. They concluded that the metasomatized peridotites could not be regarded as fragments of the source of Nunivak basalts, as had been concluded by Menzies and Murthy (1980a, b).

Two samples from St. Lawrence Island were analyzed for SIR and NIR by von Drach and others (1986). SIR are slightly higher and NIR slightly lower than those of Nunivak, but also fall in the field for ocean-island basalts.

The data of Table 1 show a small increase in SIR and decrease in NIR in the order Pribilofs, Nunivak, and St. Lawrence. This may correlate with distance from the Aleutian arc or from the edge of the Bering Shelf, or it may be fortuitous based on limited data.

*Bering Sea summary:* Bering Sea lavas of the abyssal plain (1 sample) show the isotopic character of ocean-ridge basalt. Rocks from the islands on the Bering Sea shelf show the isotopic character of ocean-island basalts and may be derived from a mantle that was zoned by metasomatism less than 200 m.y. ago. The relation of peridotite inclusions to magma sources is disputed. Small changes in the isotopic composition of the island magmas occur with increasing distance from the shelf edge or from the Aleutian arc, and with decreasing distance from the continental shorelines.

### *Mount Edgecumbe volcanic field*

The Edgecumbe volcanic field of Kruzof Island lies on the Chugach terrane of the North American plate near its transform-fault boundary with the Pacific plate (Silberling and others, this volume). The rocks range in $SiO_2$ content from 47 to 72 weight percent, are dominantly basaltic (about 70 percent), and display a gap in $SiO_2$ content in the mid-60s. Myers and Marsh (1981) reported a few SIR and several whole-rock $\delta^{18}O$ values that showed a general increase from basalt to rhyodacite. They suggested that little fractional crystallization was apparent and that the variation from mafic to silicic comoposition was best explained by adding varying amounts of crustal melts to a basalt magma.

Kosco (1981) subdivided the Edgecumbe volcanics into tholeiitic and calc-alkaline suites. He suggested that crystal fractionation produced the variety of tholeiitic basalt having SIR near 0.703. He explained calc-alkalic basaltic-andesites, andesites, and dacites having SIR near 0.7037 as a second generation of magmas from a distinct mantle source, and thought these magmas evolved in an open system by crystal fractionation and by mixing with melts from the country rock.

Myers and others (1984) reported SIR of 34 Edgecumbe samples that have a range of 0.7029 to 0.7041. Most samples are in the range of 0.7032 to 0.7039, but plagioclase basalts have lower values (0.7029 to 0.7030) and some andesites have higher values (0.7040 to 0.7041). They suggested an origin for the suite by interaction of primary plagioclase-basalt magma with crustal contaminants that changed composition over time and were melts from older granitic rocks. They suggested that rhyodacites were mixtures of small amounts of basalt and the first, most siliceous, melts from the older granitic rocks, and that intermediate andesites would be produced by mixing of basalts with subsequent and more refractory melts from the older granitic rocks.

Myers and Sinha (1985) made 22 PIR analyses on the samples previously analyzed for SIR. As was observed for SIR, the PIR values were the lowest for plagioclase basalts, highest for some andesites, and intermediate for the remaining basalts through rhyodacites. Myers and Sinha suggested a revised model in which a hypothetical parent magma collects within the crust and interacts along its borders with a variety of country rocks to produce localized pools of hybrid intermediate to silicic magmas. The hypothetical parent magma pool is then contaminated by olivine basalt and mixed to produce the observed plagioclase basalt. Subsequent eruptions tap the localized pools and the principal magma chamber to produce the observed variety of lavas.

*Mount Edgecumbe summary:* Holocene lavas of Mount Edgecumbe include at least two types of basalt and a variety of more evolved magmas that were produced when mafic magmas interacted with crustal melts.

### *Late Cretaceous and Tertiary volcanism, mainland Alaska*

Calc-alkalic to alkalic volcanism in a wide subduction-related arc occurred on mainland Alaska during the Late Cretaceous to Early Tertiary (75 to 48 Ma) in the Alaska Range, Talkeetna Mountains, Kuskokwim Mountains, and Yukon-Koyukuk basin (Moll-Stalcup, this volume). The isotopic composition of five volcanic fields in and near Yukon-Koyukuk basin was reported by Moll-Stalcup and Arth (1989). The objective of their study was to delimit the origin of the volcanic rocks and thereby identify the nature of the crust beneath the basin. Three of the volcanic fields (Blackburn Hills, Kanuti, and Yukon River) lie within the basin, and two (Sischu and Nowitna) overlie bordering Precambrian and Paleozoic metamorphic terranes to the southeast.

The volcanic fields within Yukon-Koyukuk basin have SIR of 0.7033 to 0.7052 and NIR of 0.5125 to 0.5129. Moll-Stalcup and Arth (1989) suggested that primary magma sources included oceanic mantle, and the mafic lower portions of the late Paleozoic and Mesozoic igneous assemblage of Koyukuk terrane. Based on these findings, they suggested that the Yukon-Koyukuk basin had no cratonal roots under its southeastern part. Blackburn Hills rocks (65 to 56 Ma) were subdivided into four groups, including Group 1 and Group 2 basalts and andesites, western rhyolites, and central and eastern granite intrusions. Moll-Stalcup and Arth found Group 1 compatible with an origin from ocean-island-type mantle and a small component of either ocean-floor sediment or the mafic lower crust of Koyukuk terrane. Group 2 rocks are interpreted as partial melts of the lower crust of Koyukuk terrane. Western rhyolites are proposed to be crystal fractionates of Group 1 and Group 2 magmas, or melts from the crust of Koyukuk terrane. Central and eastern granites may either be fractionates of Group 1 andesites, or melts of young mafic to intermediate crust. The Kanuti volcanic field (60 to 56 Ma) is largely dacite. Moll-Stalcup and Arth (1989) suggested an origin by melting of mafic to intermediate rocks in the lower crust of Koyukuk terrane or by fractionation of mafic magmas like those of Group 2 in Blackburn Hills. The Yukon River field (53 to 48 Ma) is a diverse collection of basalt through rhyolite and latite. Moll-Stalcup and Arth suggested that diverse processes led to the origin of these magmas from sources in the mantle and Mesozoic crust of both Koyukuk terrane and Angayucham-Tozitna terrane (an ophiolitic assemblage).

The Sischu volcanic field (71 to 66 Ma) overlies the Nixon Fork and Minchumina terranes (Silberling and others, this volume) where Precambrian to Paleozoic basement is exposed. The volcanic rocks are chiefly dacite and rhyolite, and there is minor andesite. They have SIR of 0.7075 to 0.708 and NIR of 0.5124 to 0.5125, reflecting involvement of old continental crust in their genesis (Moll-Stalcup and Arth, 1989).

The Nowitna volcanic field (66 to 63 Ma) is largely andesite and overlies three terranes: the Innoko terrane of Paleozoic to Mesozoic, oceanic sedimentary and igneous rocks; and the Ruby and Nixon Fork terranes that contain Precambrian to Paleozoic basement rocks. The Nowitna volcanic rocks have SIR of 0.7043 to 0.7051, and NIR are 0.5125 to 0.5126. Moll-Stalcup and Arth (1989) suggested a hybrid source consisting of oceanic and old continental rocks.

## MAJOR MESOZOIC TO CENOZOIC BATHOLITHS

### *The Coast batholith of southeastern Alaska*

The Coast batholith (or Coast Plutonic Complex of Canadian geologists) is the largest North American batholith and consists dominantly of plutons of quartz diorite to granite of Paleocene and Eocene age that intrude older ortho- and paragneisses. In the southeastern Alaska panhandle the plutons have been isotopically studied to the north in the Skagway area and to the south in the Ketchikan area (Table 2).

Skagway area plutons were analyzed for oxygen and hydrogen isotopes by Margaritz and Taylor (1976a). They found high values of $\delta^{18}O$ in quartz (9.7 to 11.5 per mil) in orthogneiss and tonalite of Skagway and suggested that the magmas either interacted with or assimilated high-$\delta^{18}O$ metasediments or weathered volcanic rocks. Some samples had low $\delta D$ values and anomalous differences between the $\delta^{18}O$ of quartz and feldspar, indicating that meteoric water circulated through the intrusive rocks to depths of several kilometers after the plutons crystallized.

Barker and others (1986) reported SIR in the range 0.7048 to 0.7060 on five tonalitic to granitic plutons from the Skagway area. They note that these values are within the range of many orogenic andesitic suites, and also within the range expected in the country rocks surrounding the batholith, which consist of immature sedimentary rocks, island-arc volcanic rocks, and rift and intraplate basalts. The SIR values are low enough to suggest that the sources contained little, if any, radiogenic continental rocks of pre-Mesozoic age. Barker and others (1986) suggest that the magmas had a hybrid source consisting of subduction-related basalts and melts from the country rock.

Arth and others (1988) measured SIR and NIR in the major intrusive bodies of the Coast batholith near Ketchikan. The bodies include 55- to 57-Ma foliated tonalites on the west side of an Early Cretaceous or older migmatitic orthogneiss complex, and 52- to 54-Ma massive granodiorites and granites on the east side of the gneisses. The central orthogneisses have SIR in the range 0.7053 to 0.7066 (Arth and Barker, unpublished data), and are thought by Barker and Arth (1984) to be the roots of an Early Cretaceous continental-margin magmatic arc. The western tonalites have uniform SIR of 0.7063 to 0.7064 and NIR of 0.5123 to 0.5124 and are thought by Arth and others (1988) to have been generated from sources that included significant amounts of melt from mafic parts of the central orthogneisses. The eastern granodiorites and granites have SIR of 0.7046 to 0.7061 and NIR of 0.5124, and were probably generated by mixing and fractionation of subduction-related magmas with melts from Phanerozoic crustal rocks of intermediate to silicic composition.

West of Coast batholith, plutons of quartz diorite to tonalite are of distinct age and origin (Arth and others, 1988), and are discussed below in the section on Taku terrane. Arth and others (1988) suggest that the juxtaposition of the island-arc-like Taku terrane against the older magmatic arc (central gneisses) in early Tertiary time may have triggered the generation of the 57- to 52-Ma plutons of Coast batholith.

Several small mid-Tertiary granite bodies in the Ketchikan area intrude both Coast batholith and the Taku terrane. Based on SIR and NIR values, Arth and others (1988) suggested that these granites do not represent a further evolution of Coast batholith magmas, but instead reflect an origin from more primitive sources like those of Taku terrane. These observations provide evidence that Taku rocks underlay at least part of Coast batholith by mid-Tertiary time.

*Coast batholith summary:* The central gneisses of Coast batholith are probably the eroded remnant of an Early Cretaceous continental-margin magmatic arc. In early Tertiary time, foliated tonalites intruded along the western flank of the gneisses, and massive granodiorite and granite plutons intruded to the east. The tonalites formed from sources that included significant contributions of melt from mafic parts of the gneisses; whereas the granodiorites and granites probably formed by mixing of subduction-related mafic magmas with magmas derived by melting of metasedimentary, metavolcanic, and metaplutonic country rocks in which Precambrian rocks were absent or scarce. Some of the plutons experienced circulation of meteoric water after crystallization. The batholith probably formed at the time that Taku terrane was joined to North America at the site of an Early Cretaceous continental-margin arc.

### *The Alaska–Aleutian Ranges batholith of south-central Alaska*

The Alaska–Aleutian Ranges batholith of south-central Alaska is one of the major circum-Pacific batholiths. Reed and Lanphere (1973) showed that it resulted from distinct intrusive episodes in Jurassic, Late Cretaceous to early Tertiary, and middle Tertiary time.

The southern and eastern part of the batholith is mostly Jurassic (158 to 174 Ma) quartz diorite and tonalite but varies from gabbro to granite. The rocks have SIR of 0.7033 to 0.7037 (M. A. Lanphere and B. L. Reed, unpublished data cited by Reed and others, 1983), values that are similar to those of oceanic island arcs. Reed and others (1983) suggest that these rocks formed the root of an oceanic island arc that was accreted to Alaska during late Mesozoic time.

The western and northern part of the batholith is composed principally of Late Cretaceous to early Tertiary (76 to 59 Ma) tonalite, granodiorite, and granite, as well as middle Tertiary (38 to 26 Ma) tonalite, granodiorite, and granite. Lanphere and Reed (1985) published SIR and $\delta^{18}O$ data on five McKinley-sequence, peraluminous, "minimum-melt" granite plutons of Paleocene age that constitute a small part of the Late Cretaceous to early Tertiary suite. These plutons largely intrude deformed upper Mesozoic flysch in the central Alaska Range. SIR range from 0.7054 to 0.7085 and $\delta^{18}O$ range from +11.2 to +14.6. The four plutons southeast of the Denali fault have SIR of 0.7054 to 0.7065, whereas a pluton northwest of the fault has SIR of 0.7071 to 0.7081. No polarity was observed in the oxygen ratios. Lanphere and Reed (1985) compared SIR in the granite with SIR in the flysch and found that simple melting of the flysch would produce granite of higher SIR than they observed. They suggested that mafic magma having lower SIR assimilated flysch to produce hybrid magmas that subsequently were fractionally crystallized. The pluton to the north of the Denali fault reflects assimilation of more radiogenic Precambrian or Paleozoic metasedimentary and metavolcanic rocks. They ascribed deformation of the schist belt and generation of magma to the tectonic event that produced accretion of the Talkeetna superterrane to stable Alaska in latest Cretaceous to early Tertiary time.

### *The Ruby batholith of central Alaska*

A large percentage of outcrop in the Ruby geanticline in central Alaska is composed of Albian (~ 110 Ma) granitic intrusive rocks (Ruby batholith), which form a belt more than 350 km long (Patton and others, this volume, chapter 6). Most of these granitic plutons intrude Precambrian and Paleozoic schists and lesser orthogneisses, marble, quartzite, and amphibolite of the

Ruby terrane (Plate 3, this volume); a few intrude Paleozoic to Mesozoic oceanic rocks of the Angayucham terrane. The plutons consist dominantly of coarse-grained biotite and two-mica granites, most of which are feldspar porphyritic. Biotite-hornblende granodiorite occurs in the northeastern part of the batholith, as does a small pluton of monzonite and syenite near Jim River (Barker and others, this volume).

Arth and others (1984) determined SIR, PIR, and $\delta^{18}O$ values in four plutons in the center of the batholith near Kanuti, Hot Springs, and Sithylemenkat, and in the Ray Mountains. High values of SIR (0.706 to 0.730), $\delta^{18}O$ (>8.5), and PIR7 (15.54 to 15.70) led these authors to suggest that granite magmas of the geanticline either formed from—or incorporated large amounts of—continental crust of Paleozoic or greater age.

Blum and others (1987) reported SIR and $\delta^{18}O$ for Jim River and Hodzana plutons at the northeastern end of the batholith. They determined SIR of 0.7078 and 0.7079, respectively, in monzonitic and granitic rocks, and a range in $\delta^{18}O$ from +6.8 to +7.3 per mil. They suggested that monzonite was a primary magma formed in the lower crust or mantle, whereas granite magma may have formed when monzonite magma assimilated upper crustal melts.

Arth and others (1989a) reported SIR, NIR and $\delta^{18}O$ for all plutons of the batholith. They noted that SIR and NIR show a trend along strike from southwest to northeast, but that $\delta^{18}O$ has a constant range of +8.4 to +11.8 per mil. Rocks to the southwest have the highest SIR (0.7235) and lowest NIR (0.51150), whereas those to the northeast have the lowest SIR (0.7055) and highest NIR (0.51232). Some individual plutons show uniform isotopic values, whereas others show a range. Arth and others (1989a) suggested that isotopically uniform plutons underwent fractional crystallization; isotopically heterogeneous plutons were possibly affected by magma mixing and assimilation. The source for most of the magmas was within the deeper parts of the Proterozoic to Paleozoic crust that underlay both Ruby and Angayucham terranes at 110 Ma, and was probably lithologically similar to the presently exposed country rock of Ruby terrane. The source rocks were probably heterogeneous in age and composition, varying from Proterozoic to Paleozoic, and from silicic orthogneisses and schists to mafic to intermediate metaigneous rocks. The strong isotopic trends in the batholith may be related to changes in the proportions of the source rocks along strike under the batholith. Sources to the southwest were dominantly silicic and included both Paleozoic and Proterozoic rock, whereas those to the northeast were mostly Paleozoic and contained a higher proportion of mafic to intermediate rocks.

## MAGMATIC SUITES OF ECONOMIC INTEREST

In addition to the major Mesozoic to Cenozoic volcanic provinces and batholiths discussed above, Alaska contains many other igneous suites of Mesozoic and Cenozoic age. Three suites that are of economic interest are discussed in this section. In the next section, many additional suites are discussed in relation to the tectonostratigraphic terrane in which they are located.

### *Duke Island–type ultramafic rocks, southeastern Alaska*

More than 35 ultramafic complexes and associated gabbros form a belt about 50 km wide and 560 km long west of and parallel to the Coast batholith. These 102- to 113-Ma bodies, intruded after folding and metamorphism of the Paleozoic and early Mesozoic country rocks, are generally small and show a concentric zoning where dunite and peridotite in the core intrude successively surrounding zones of olivine pyroxenite, hornblende pyroxenite, and hornblendite. Lanphere (1968) determined SIR in four zoned bodies and found a range of 0.702 to 0.705. He noted the similarity of these values to those of oceanic volcanic rocks, and inferred that these largely cumulate rocks crystallized from magmas originating in oceanic-type mantle.

Taylor (1968) published $\delta^{18}O$ data for a variety of minerals from many of the ultramafic complexes of southeastern Alaska, and found them compatible with a magmatic origin for these rocks. $\delta^{18}O$ of clinopyroxene in various rock types has uniform values of +5.4 to +5.9 per mil. Magnetite in massive segregations has values of +3.3 to +4.4 per mil. Clinopyroxene-magnetite fractionation values of 5.1 to 2.1 per mil probably represent a close approach to equilibrium and are compatible with high-temperature magmatic crystallization (Taylor and Noble, 1969).

### *Tin granites of Seward Peninsula*

Seven Late Cretaceous granite plutons that are spatially and genetically related to tin mineralization are exposed in a 170-km-long belt across the northwestern part of Seward Peninsula, Alaska. The plutons intrude a variety of terranes that include large areas of sedimentary and metasedimentary rocks of Precambrian and Paleozoic age. The field relations, ages, petrography, chemistry, and isotopic composition of these rocks are described by Hudson and Arth (1983), who determined SIR for five of the plutons. The data for individual plutons showed Sr isotopic homogeneity among the several textural facies that make up a composite body, and demonstrated that these facies are genetically linked. The initial ratios varied from pluton to pluton in the range 0.708 to 0.720. Hudson and Arth (1983) concluded that the high values reflect a dominantly crustal source for the parent magmas. They favored a multistage origin of the tin granites that involved melting of sialic crust to produce batholithic magmas, which subsequently fractionated to generate smaller volumes of highly evolved residual magma. Evolution of the individual plutons was largely by fractional crystallization, although the final stages involved transport of elements by a coexisting volatile phase.

### *Molybdenum-bearing granites of the Ketchikan area*

Stockwork molybdenum deposits in the Ketchikan area are associated with shallow porphyritic biotite granite intrusions of late Oligocene to Miocene age. Magmatism took place in a postorogenic tectonic setting that was characterized by regional extension and possibly bimodal magmatism. Hudson and others (1981) reported SIR of 0.7051 for the Quartz Hill pluton, and

0.7049 to 0.7051 for the Burroughs Bay intrusion. The SIR of these bodies was lower than the late Oligocene to Miocene Sr isotopic ratios of the surrounding older plutons of Coast batholith and Taku terrane, or of the metamorphic country rocks. This distinction precludes a simple direct genetic relation between the molybdenum-related granites and the exposed rock around them. Hudson and others (1981) suggested a magma source region dominated by rocks of low Rb/Sr ratio, such as those in the mantle or lower crust or rapidly recycled, mantle-derived material at depths of less than 60 km. Arth and others (1988) suggested that the source was probably the deeper part of the Taku terrane, which probably underlay the whole area by mid-Tertiary time.

## IGNEOUS ROCKS IN TECTONOSTRATIGRAPHIC TERRANES

All of the igneous rocks of Alaska intrude, overlie, or are otherwise part of one or more tectonostratigraphic (lithotectonic) terranes (Silberling and others, this volume). An igneous body that intrudes country rock of a given terrane may indicate the nature of the basement of that terrane at the time of intrusion. In this section, I review the isotopic composition (Table 2) and petrogenesis of Mesozoic and Cenozoic igneous rocks in the context of their host tectonostratigraphic terranes. In the next section, I discuss the implications of the data to the nature of the lower crust under Alaska.

Each of the tectonostratigraphic terranes of Alaska is bounded by faults and has a characteristic stratigraphy that records a different geologic history from that of adjacent terranes (Coney and others, 1980). Some of the terranes are "exotic" to North America in that they were transported as crustal blocks to their present location from elsewhere, and have been "accreted" to the continent in late Mesozoic or early Cenozoic time. Identifying the nature of the basement under some tectonostratigraphic terranes can be assisted by isotopic study of the igenous rocks. Many such rocks, particularly granitic intrusions, crystallize from magmas that originated, at least in part, by melting of substantial volumes of lower crust or subcrustal mantle. Their isotopic character thus can yield information about the age and composition of this deep source region. Because the deeper crust under a given terrane may change character during accretion, the igneous rocks that intrude at various times may reflect the crustal conditions before, during, or after the time of accretion.

The terranes discussed below are those for which at least some isotopic-tracer data are available for their igneous rocks. For most of the larger terranes there are at least some data. Many of the smaller terranes have not been studied. The terranes are described from east to west in southeastern Alaska, and from south to north in mainland Alaska.

### *Tracy Arm terrane*

The Tracy Arm terrane consists largely of Paleozoic to Mesozoic schist, paragneiss, marble, amphibolite, and minor serpentinite that form roof pendants and wall rocks of the Coast batholith. These rocks may be the higher-metamorphic-grade equivalents of the Stikine terrane to the east, or of the Alexander or Taku terranes to the west. Early Tertiary plutons of the Coast batholith intrude the Tracy Arm terrane and have SIR of 0.7045 to 0.7064 and NIR of 0.5123 to 0.5124 (Barker and others, 1986, Arth and others, 1988). These plutons are discussed in the foregoing description of the Coast batholith. Arth and others (1988) suggested that the western foliated tonalites are largely the product of melting in the deeper mafic parts of the older central gneisses of the batholith, whereas the eastern granodiorites and granites are the product of mixing of subduction-related mafic magma with magmas derived by melting of metasedimentary and metaigneous country rock in which Precambrian rocks or metapelitic rocks were not abundant or absent. Thus the early Tertiary basement of this terrane was probably mostly Mesozoic orthogneisses and paragneisses. By mid Tertiary time, when small bodies of granite intruded, the basement source had a more primitive island-arc-like isotopic character similar to that found in plutons of Taku terrane (Arth and others, 1988). This change in magma sources in the basement beneath Tracy Arm terrane may reflect underthrusting by Taku terrane from the west during the early Tertiary.

### *Taku terrane*

Taku terrane is immediately west of the Coast batholith in much of southeastern Alaska. On Revillagigedo Island and the mainland to the northwest, this terrane is intruded by tonalite and quartz diorite that constitute a suite of 90-Ma plutons and one body of possibly 135 Ma. These pre-accretionary rocks intrude high-grade mafic-to-intermediate metavolcanic rocks, metagraywacke, and metapelite, and have SIR of 0.704 to 0.705 and NIR of 0.5125 (Arth and others, 1988). The low SIR suggest that little, if any, radiogenic crust (Precambrian, granitic, or pelitic) was incorporated in or contributed melt to the magmas. The moderate NIR may reflect the incorporation or contribution of some Paleozoic and younger mafic to intermediate country rock. The tonalites probably solidified from magmas of hybrid origin, consisting of mixtures of subduction-related basalt and partial melts from Paleozoic or younger country rock of mafic to intermediate composition. The Taku, thus, may represent an accreted magmatic arc. Post-accretion Tertiary granites have SIR and NIR that are similar to those of the older intrusions (Arth and others, 1988) and may have originated from similar sources. Thus the basement beneath Taku terrane is probably of Phanerozoic oceanic to island-arc character.

### *Alexander terrane*

Alexander terrane lies west of Taku terrane in much of southeastern Alaska and consists largely of Paleozoic schist and gneiss, felsic to mafic volcanic rocks, and minor pelitic rocks and carbonate (Plate 3, this volume.). On Prince of Wales Island the rocks were intruded by quartz monzonite and gabbro in late

**TABLE 2. ISOTOPIC RANGES FOR MESOZOIC AND CENOZOIC PLUTONIC ROCKS OF ALASKA**

| Location | SIR* | NIR† | References§ |
|---|---|---|---|
| **Major Mesozoic to Cenozoic batholiths** | | | |
| Coast batholith | | | |
| Western tonalites (Ketchikan area) | 0.7063–0.7064 | 0.5123–0.5124 | 1 |
| Central tonalite-granodiorite (Skagway area) | 0.7054–0.7058 | | 2 |
| Central orthogneiss suite (Ketchikan area) | 0.7053–0.7066 | | 1 |
| Eastern granodiorites and granites (Ketchikan and Skagway areas) | 0.7046–0.7061 | 0.5124–0.5124 | 1, 2 |
| Alaska-Aleutian Ranges batholith | | | |
| Southwestern Jurassic suite | 0.7033–0.7037 | | 3 |
| McKinley series (Paleocene) | | | |
| southeast of Denali fault system | 0.7054–0.7065 | | 4 |
| northwest of Denali fault system | 0.7071–0.7081 | | 4 |
| Ruby batholith | 0.7056–0.7294 | 0.5115–0.5124 | 5 |
| **Magmatic suites of economic interest** | | | |
| Duke Island-type ultramafic rocks, SE Alaska | 0.702–0.705 | | 6 |
| Tin granites of Seward Peninsula | 0.708–0.720 | | 7 |
| Molybdenum-bearing granites, Ketchikan area | 0.7049–0.7051 | | 1, 8 |
| **Plutons in tectonostratigaphic terranes** | | | |
| Chugach and Prince William terranes | | | |
| Sanak-Baranof belt pultons | 0.7048–0.7063 | | 9–12 |
| Kahiltna terrane | | | |
| McKinley series plutons, Alaska Range | 0.7054–0.7065 | | 4 |
| Koyukuk terrane | | | |
| eastern calc-alkalic suite | 0.7038–0.7056 | 0.5124–0.5126 | 13 |
| western alkalic suite | 0.7069–0.7130 | 0.5121–0.5125 | 13 |
| Peninsular terrane | | | |
| Kodiak and Afognak Islands-Jurassic | 0.7035–0.7037 | | 14 |
| Aleutian Range Jurassic suite | 0.7033–0.7037 | | 3 |
| Northern Chugach Jurassic suite | 0.7032–0.7033 | | 14 |
| Talkeetna Mountains tonalites | 0.7034–0.7037 | | 14 |
| Ruby terrane | | | |
| Ruby batholith (all) | 0.7056–0.7294 | 0.5115–0.5124 | 5 |
| Seward and York terranes | | | |
| Tin granites | 0.708–0.720 | | 7 |
| Eastern Seward Peninsula calc-alkalic | 0.7084–0.7109 | | 15 |
| Eastern Seward Peninsula alkalic | 0.712–0.715 | | 15 |
| Tracy Arm terrane | | | |
| Coast batholith | 0.7046–0.7064 | 0.5123–0.5124 | 1, 2 |
| Taku terrane | | | |
| tonalitic suite | 0.7041–0.7050 | | 1 |
| Wrangellia terrane | | | |
| Chitina Valley batholith | 0.7038–0.7045 | | 14 |
| Yukon-Tanana terrane | | | |
| Gilmore Dome | 0.7124 | | 16 |

*All ratios normalized to $^{86}Sr/^{88}Sr = 0.11940$.

†All ratios normalized to $^{146}Nd/^{144}Nd = 0.72190$

§1. Arth and others, 1988; 2. Barker and others, 1986; 3. Reed and others, 1983; 4. Lanphere and Reed, 1985; 5. Arth and others, 1989a; 6. Lanphere, 1968; 7. Hudson and Arth, 1983; 8. Hudson and others, 1981; 9. Hudson and others, 1979; 10. Hill and others, 1981; 11. Myers and Marsh, 1981; 12. Kosco, 1981; 13. Arth and others, 1989b; 14. Arth and Hudson, unpublished data; 15, Arth, 1987; 16. Blum, 1985.

Ordovician to Early Silurian time (Lanphere and others, 1964). A Rb-Sr isochron study of these plutons by Armstrong (1985) gave an SIR of 0.7039, consistent with their emplacement in a Phanerozoic volcanic arc. No younger plutons are as yet isotopically characterized, so that the basement is tentatively considered to be of oceanic-arc character.

### *Chugach and Prince William terranes*

Along the margin of the Gulf of Alaska, the Sanak-Baranof belt of early Tertiary granitic plutons intrudes a prism of flyschoid rocks that were accreted to the continental margin during Late Cretaceous or early Tertiary time (Hudson and others, 1979; Hudson, this volume). The plutons include biotite tonalite, granodiorite, and granite that are generally homogeneous, medium grained, and equigranular. Hornblende is generally absent, and white mica and garnet are present locally. Kyanite megacrysts occur in some plutons on Kodiak Island in the western part of the belt.

Hudson and others (1979) studied plutons and metamorphic country rocks of the Sanak-Baranof belt in the eastern Chugach and St. Elias Mountains. They showed that two 50-Ma granodiorites had SIR (0.7059 and 0.7063) that were close to the age-corrected Sr isotopic composition of two metagraywacke samples (0.7061 and 0.7062). Metasandstone and amphibolite, respectively, showed higher and lower values. Hudson and coworkers concluded that the granitic magmas are partial melts of the deeper parts of the accretionary prism and were generated after the prism was deformed against the continent.

Hill and others (1981) conducted an extensive geochemical study on plutons of about 60 Ma on Kodiak, Shumagin, and Sanak Islands in the western part of the Sanak-Baranof belt. The plutons are characterized by high $\delta^{18}O$ values of +10.9 to +13.2 per mil, which are similar to the values found in nearby graywacke, lower than those of nearby argillite, and presumably higher than those of local greenstone. SIR for the Shumagin batholith and Sanak pluton are about 0.7053, as estimated from mineral isochrons of about 60 Ma. At 60 Ma, the nearby flysch belt had $^{87}Sr/^{86}Sr$ ratios of 0.7046 to 0.7050 in graywacke and 0.7061 to 0.7089 in argillite. Hill and others (1981) calculated the proportion of sediment to mafic metavolcanic rocks needed to satisfy the Sr and O isotopic constraints, and concluded that the proportion of amphibolite required for melting was not present in the accreted prism. Therefore, they suggested that mantle-derived basalt magma was added to the prism to produce the observed compositions. The authors relied for their models on a $\delta^{18}O$ value of +10.6 per mil found in amphibolites of the Franciscan Complex in California (Margaritz and Taylor, 1976a). If nearby mafic volcanic rocks in the Sanak-Baranof belt have a lower $\delta^{18}O$ value, then much less mafic component would be required to model the granites, and the flysch belt alone may constitute an adequate source.

A granodiorite pluton on Kruzof Island near Sitka was intruded at about 50 Ma into Sitka graywacke of the Chugach terrane. The pluton is overlain by Holocene volcanic rocks of the Edgecumbe volcanic field. Myers and Marsh (1981) and Kosco (1981) measured SIR of about 0.7048 in the granodiorite. Myers and Marsh (1981) also measured $\delta^{18}O$ of 8.7 to 9.3 per mil in the granodiorite. The authors did not comment on the genesis of the pluton, but the values reported are compatible with an origin by melting of country rock or by mixing of country-rock melt and mafic magma, as hypothesized for other plutons in the Sanak-Baranof belt.

*Chugach and Prince William summary:* Tonalite-to-granite plutons of the early Tertiary Sanak-Baranof belt were probably derived by melting of deep parts of the accreted Chugach–Prince William terranes of Late Cretaceous or early Tertiary graywacke, argillite, and mafic volcanic rocks. An additional basalt component may have mixed with the crustal melts to produce the plutons.

### *Peninsular terrane*

The Peninsular terrane of southwestern and south-central Alaska consists of Permian limestone; Upper Triassic limestone, argillite and volcanic rocks; Lower Jurassic andesitic volcanic rocks; and Middle Jurassic to Cretaceous clastic rocks. Jurassic plutons, largely tonalitic, are found in the Alaska–Aleutian Range batholith, on northern Kodiak Island, in the northern Chugach Mountains east of Anchorage, and in the Talkeetna Mountains.

Reed and others (1983) cite SIR of 0.7033 to 0.7037 in the southeastern part of the Alaska–Aleutian Range batholith (158 to 174 Ma). They consider this part of the batholith to be the root of an oceanic island arc.

Arth and Hudson (unpublished data) determined SIR values of 0.7033 to 0.7037 for 180- to 190-Ma plutons on Kodiak Island and in the northern Chugach Mountains, and values of 0.7034 and 0.7037 in tonalites of the Talkeetna Mountains. Hudson and others (1985) interpreted the Kodiak and Northern Chugach plutons to be a tholeiitic suite in a Jurassic island arc, and the Talkeetna Mountains tonalites to be part of a calc-alkalic suite in a Jurassic arc.

From the studies noted above, it appears that much of the Peninsular terrane is underlain by Mesozoic island-arc rocks. It should be noted that these rocks also underlay the eastern volcanoes of the Aleutian magmatic arc. Several studies of Aleutian volcanic rocks, discussed in the section of this chapter on Cenozoic volcanic provinces, did not reveal any "continental" component in the eastern Aleutian-arc magmas. However, no significant isotopic changes should accompany assimilation of "continental" rocks in the deeper parts of the Peninsular terrane, because the rocks are isotopically very similar to oceanic magma sources in the western Aleutians.

### *Wrangellia terrane*

The Wrangellia terrane of east-central and southeastern Alaska is an upper Paleozoic volcanic-arc suite overlain by Permian limestone, pelite, and chert; Triassic subaerial basalt and

overlying platform carbonate; and Mesozoic marine sedimentary rocks. Several Late Jurassic granite plutons of the Chitina Valley batholith, near the Canadian border, have SIR of 0.7038 to 0.7045 (Arth and Hudson, unpublished data), and may indicate a mafic source at depth. Aleinikoff (1984) reports that undated granites south of the Denali fault have PIR7 ratios of 15.52 to 15.57, which he finds suggestive of an oceanic source.

### *Yukon-Tanana terrane*

The Yukon-Tanana terrane of east-central Alaska is composed mainly of Precambrian to Paleozoic polydeformed rocks, including quartz-mica schist and gneiss, quartzite, metavolcanic and metaplutonic rocks, and minor marble. Published isotopic data on Cretaceous plutons are limited. Blum (1985) determined a SIR of 0.7124 in a small 91-Ma porphyritic granodiorite-to-granite pluton of Gilmore Dome near Fairbanks. He suggested that the magma formed, at least in part, by anatectic melting of late Proterozoic or early Paleozoic crustal rocks.

Aleinikoff (1984) reported that Cretaceous plutons in several small terranes north of the Denali fault (Lake George, Macomb, Jarvis Creek, and Hayes Glacier) have PIR7 of 15.61 to 15.72, indicating a mixture of lead from both continental and oceanic sources. He also determined that Cretaceous plutons in the Maclaren terrane, just south of the Denali fault, have PIR7 of 15.56 to 15.60, suggesting derivation from an oceanic source with minor crustal input.

### *Ruby and Nixon Fork terranes*

The Ruby and Nixon Fork terranes include Precambrian to Paleozoic pelitic and calcareous schists, orthogneisses, marble, quartzite, and metavolcanic rocks. Nixon Fork terrane contains a sequence of Paleozoic carbonates overlain by Permian, Triassic, and Cretaceous sedimentary rocks. The Ruby terrane is host to the Ruby batholith of Cretaceous granitic plutons, whose isotopic character is very radiogenic, reflecting a source in Proterozoic and Paleozoic continental crust (Arth and others, 1989a). The Ruby batholith is discussed in more detail in the section of this chapter on major batholiths.

The Nixon Fork terrane is host to the Sischu volcanic field, composed of rhyolite, dacite, and lesser andesite. The volcanic rocks have SIR of 0.7079 to 0.7141 and NIR of 0.5124 to 0.5125, reflecting magma generation involving old continental crust (Moll-Stalcup and Arth, 1989). Thus, both the Ruby and Nixon Fork terranes are probably underlain by continental rocks.

### *Koyukuk terrane and Yukon-Koyukuk basin*

The Koyukuk terrane is an arcuate belt of Early Cretaceous volcanic rocks flanked by Upper Cretaceous flysch deposits in the vast Yukon-Koyukuk basin of west-central Alaska (Patton and Box, 1989). The basin is bordered by highlands of metamorphosed Precambrian and Paleozoic rocks of the Brooks Range, Seward Peninsula, and the Ruby geanticline. Two suites of plutonic rocks intrude the basin: a western alkalic suite of 100- to 113-Ma quartz monzonite, monzonite, syenite, and ultrapotassic subsilicic rocks; and an eastern calc-alkalic suite of 79- to 89-Ma tonalite, granodiorite, granite, and alaskite (Miller, 1989).

Arth and others (1984) reported SIR, NIR, PIR, and $\delta^{18}O$ on two granodiorite-to-tonalite plutons (Indian Mountain and Zane Hills). The plutons have low SIR (0.7038 to 0.7047), low PIR7 (15.50 to 15.53), and low $\delta^{18}O$ ($<8.5$) compared with Cretaceous granites in the adjacent borderlands (see descriptions of Ruby batholith and Seward terrane sections in this chapter). These values are characteristic of island-arc or convergent continental-margin magmatic suites in which tonalite to granodiorite may be generated by fractionation or melting of mafic volcanic rocks. Isotope data for these two plutons do not support the presence of Paleozoic or older continental crust below the eastern part of the Yukon-Koyukuk basin.

Arth (1985) reported the range of SIR and NIR for five plutons that form an east-to-west belt across the eastern half of the basin. From east to west (Indian Mountain to Purcell Mountains), the rocks become more potassic (from tonalite to granite), increase in SIR from 0.7038 to 0.7056, and have decreasing NIR from 0.51261 to 0.51245. The values were considered compatible with sources that may include oceanic mantle and Mesozoic supracrustal rocks. The isotopic variations would reflect an east-to-west increase in the degree of crustal involvement in magma generation.

In the western suite, the SIR and NIR of the potassic alkalic plutons display a continuation of the east-to-west trends of the plutons in the eastern suite. Arth (1987) reported SIR of 0.7069 to 0.7130 and NIR of 0.5125 to 0.5121. He ascribed the generation of the alkalic magmas to melting of Paleozoic and Precambrian subcontinental-type mantle, accompanied by interaction with rocks in the overlying lower crust.

Arth and others (1989b) reported isotopic and trace-element data for all plutons of the belt and noted remarkably continuous trends in isotopic ratios and concentration of several trace elements along the full 350-km length of the plutonic belt, from potassic alkalic plutons on the west through sodic calc-alkalic plutons in the east. From west to east, SIR vary from 0.712 to 0.704; NIR from 0.5121 to 0.5126; and $\delta^{18}O$ from +8.6 to +6.5. Arth and others (1989b) inferred from the chemical and isotopic features that the westernmost plutons originated by melting or fractionation in a Paleozoic or older continental section that included mantle and perhaps crustal rocks; that the easternmost plutons originated by melting or fractionation of mafic rocks of Mesozoic oceanic to island-arc affinity; and that plutons found between the eastern and western ends of the belt experienced individual fractionation histories, but their sources vary gradationally across the width of the basin in the proportion of older continental (mantle and crustal) and Mesozoic oceanic or island-arc rocks.

Moll-Stalcup and Arth (1989) reported SIR and NIR of three mid-Tertiary volcanic fields (Kanuti, Yukon River, and

Blackburn Hills) that lie along the southeastern margin of Yukon-Koyukuk basin. The low values for SIR (0.7037 to 0.7051) and high values for NIR (0.5125 to 0.5128) suggest sources within oceanic mantle or Mesozoic island-arc rocks.

From the foregoing studies, it appears that the Yukon-Koyukuk basin is underlain by continental lithosphere from its margin at Seward Peninsula eastward to about longitude 157°. East of this parallel and in a band at least 50 km wide along its southeastern margin, the basin is probably underlain by rocks of oceanic to island-arc character.

### *Seward and York terranes*

The Seward Peninsula is largely composed of complex schists and gneisses of Precambrian to Devonian age (Seward terrane), and an assemblage of Precambrian(?) to Paleozoic metasedimentary rocks (York terrane). Igneous suites include Cretaceous tin-bearing granites, calc-alkalic intrusive rocks, and alkalic intrusive rocks.

The tin-granite suite intrudes the northwestern part of the peninsula and has high SIR, reflecting a source in the continental crust (Hudson and Arth, 1983). It is discussed separately in the economic section of this chapter.

Arth (1987) reported SIR of 0.708 to 0.711 in the 82- to 96-Ma calc-alkalic suite of eastern Seward Peninsula, including the Darby and Bendeleben plutons. He suggested generation within Precambrian to Paleozoic crustal rocks.

Arth (1987) reported that 99- to 113-Ma alkalic plutons of eastern Seward Peninsula (including Kachauik batholith and Dry Canyon Creek pluton) and the adjacent Yukon-Koyukuk basin have SIR of 0.707 to 0.713, and NIR of 0.5125 to 0.5121. He suggested an origin by melting in the Precambrian to Paleozoic continental mantle accompanied by interaction with rocks in the overlying crust.

From the studies cited above, it appears that most parts of Seward Peninsula are underlain by continental lithosphere of probable Precambrian to Paleozoic age.

## A MAP OF THE DEEP CONTINENTAL CRUST BASED ON SIR OF IGNEOUS ROCKS

Figure 1 is a map of Alaska on which I infer the nature of the deep continental crust from the compositional and isotopic studies cited above. The magmas that formed many of the granitic and intermediate-to-silicic volcanic rocks were partly or totally produced within the deep crust, and therefore carry with them the isotopic signature of the materials that constitute that crust.

Among the isotopic data discussed in this chapter, only Sr ratios have been measured on enough samples to provide a geographically balanced data set that is adequate to characterize the general features of the deep Alaskan crust. In a manner analogous to the division of California plutons by Kistler and Peterman (1973), I divide Alaska plutons into three groups based on their SIR. The bounding SIR values for the groups are chosen on the basis of the genetic inferences made by the investigators who obtained and interpreted the petrologic, isotopic, and chemical data in each terrane. SIR values in the 0.702 to 0.705 range characterize igneous rocks formed largely from Paleozoic and younger rocks of generally oceanic character, such as the roots of island arcs. SIR values more than 0.708 characterize igneous rocks that formed largely from ancient continental lithosphere, such as Precambrian-to-Paleozoic crustal cratonic rocks and continental mantle. SIR values that fall between these two groups, in the range 0.705 to 0.708, characterize igneous rocks that formed either by melting of Paleozoic and Mesozoic flysch and melange or by mixing of oceanic and ancient continental sources.

Figure 1 depicts the three isotopic subdivisions and also shows the major faults and tectonostratigraphic terranes of Alaska. Areas of the figure shown in a dark stippled pattern have igneous rocks that have SIR higher than 0.708 and largely correspond to the parts of Alaska where Precambrian to Paleozoic rocks are exposed. I refer to the deep crust under these areas as Cratonia. Northern Cratonia, underlying Seward Peninsula and the Ruby Geanticline, is inferred from isotopic measurements on a large number of plutons. Central Cratonia, underlying the Nixon Fork and Yukon-Tanana terranes, is inferred from very limited data.

Areas shown in a light stipple pattern have igneous rocks that have SIR of less than 0.705, and largely correspond to parts of Alaska where Paleozoic to Mesozoic magmatic-arc and oceanic-type rocks are exposed. I refer to the deep crust under these areas as Volcania. Northern Volcania underlies the eastern and southern part of the Yukon-Koyukuk basin and is inferred from a large number of measurements. Southern Volcania underlies the rocks of Wrangellia and the Peninsular terranes, which have marked island-arc and oceanic affinities, and is inferred from a substantial number of measurements scattered throughout the area. Southeastern Volcania underlies the Taku terrane, which contains many volcanic and plutonic rocks that appear to be of magmatic-arc association. It is inferred from several measurements in the Ketchikan area.

Areas shown in a dot pattern have igneous rocks in the SIR range of 0.705 to 0.708 and largely correspond, with one exception, to parts of Alaska where Phanerozoic flysch belts are exposed. I refer to the basement under these areas as Detritia. Southern Detritia underlies the combined Chugach and Prince William terranes, which consist of Jurassic to Lower Tertiary flysch, melange, and minor mafic volcanic rocks. It is inferred from measurements on several plutons at widely separated localities along the length of the Sanak-Baranof plutonic belt. Central Detritia primarily underlies the Kahiltna terrane of Upper Jurassic to Cenomanian flysch. Eastern Detritia primarily underlies the Tracy Arm terrane and may include some areas under the Stikine terrane. It is inferred from measurements of the Coast batholith in the Ketchikan and Skagway areas and in Canada.

The only area of plutons having SIR of 0.705 to 0.708 that is probably not underlain by flysch is in the central part of the Yukon-Koyukuk basin. The intermediate SIR values in that re-

gion probably represent a transition from low-SIR calc-alkalic plutons of eastern Yukon-Koyukuk basin to alkalic high-SIR plutons of western Yukon-Koyukuk basin. The eastern plutons are probably related to melting of oceanic or island-arc-derived rocks, whereas the western Yukon-Koyukuk plutons may be generated in old continental lithosphere. Rocks in the central zone may reflect mixtures of these sources and may be underlain by deep crust and mantle of continental type (Cratonia) and deep crust of oceanic or island-arc type (Volcania).

The subdivision of the deep crust of Alaska into these three types leads to some interesting thoughts about the myriad tectonostratigraphic terranes that have been proposed in the upper crust (Plate 3, this volume). Most of the lower-crustal source rocks inferred from the isotopic and petrologic data are of the

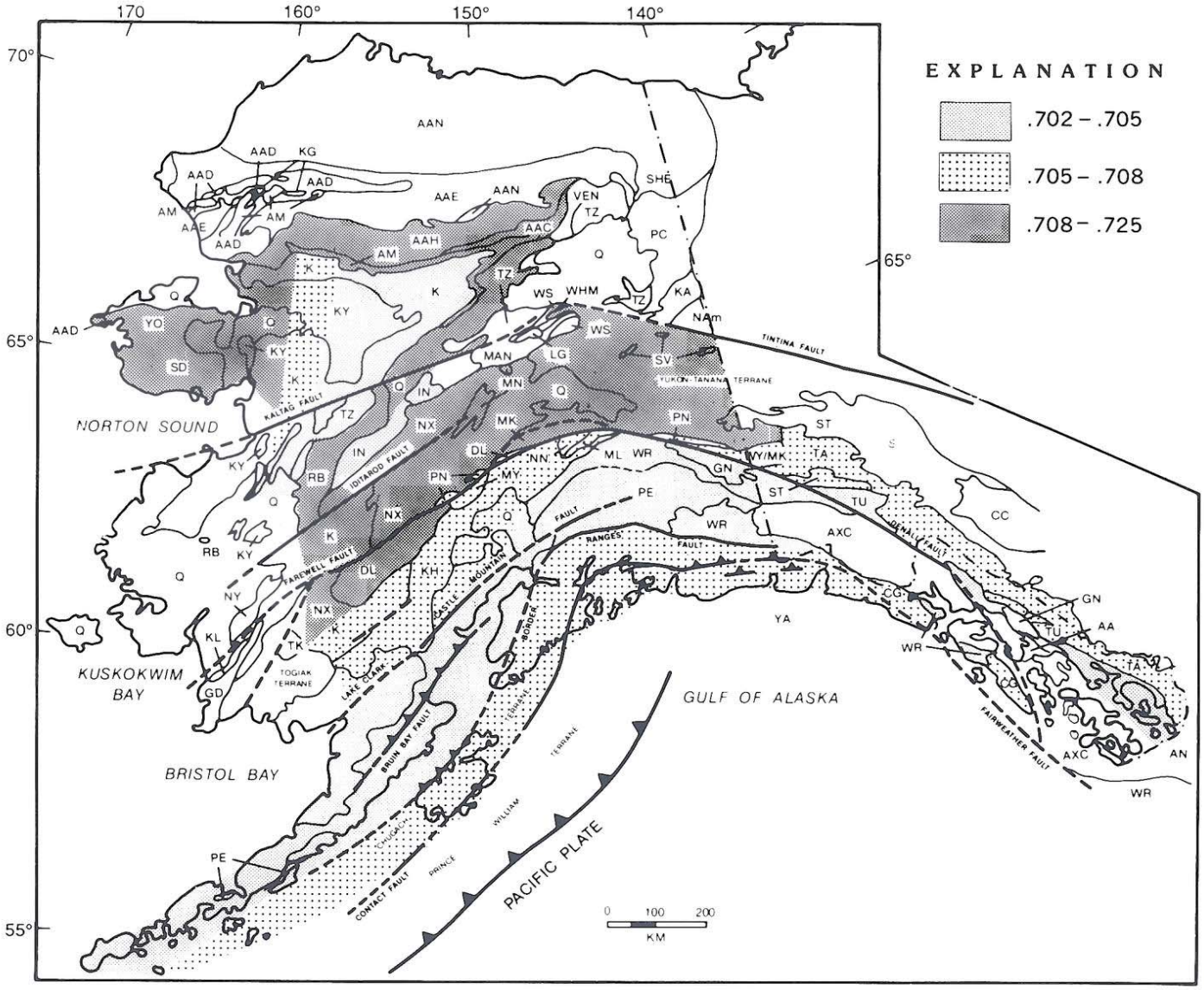


Figure 1. Map of Alaska showing the three types of lower crust inferred from the initial Sr isotopic ratios (SIR) and other geochemical data on the Jurassic to Tertiary igneous rocks. Areas shown in dark stipple have SIR of more than 0.708. They are underlain by Precambrian to Paleozoic continental lithosphere and are here called Cratonia. Areas shown in light stipple have SIR of 0.702 to 0.705 and are underlain by island-arc to oceanic lower crust, here called Volcania. Areas shown in a dot pattern have SIR of 0.705 to 0.708 and are underlain by infolded flysch belts, here called Detritia (except in the Yukon-Koyukuk basin where they are underlain by a mixture of Volcania and Cratonia). The major faults and tectonostratigraphic terranes are shown for reference. Many of the terranes are designated by abbreviations, including: Alexander—AXC, Angayucham—AM, Koyukuk—KY, Nixon Fork—NX, Peninsular—PE, Ruby—RB, Seward—SD, Taku—TU, Tracy Arm—TA, Wrangellia—WR, and York—YO.

same composition as the rock types that dominate the overlying, upper crustal terranes. The upper crust, thus, may be genetically linked to the lower crust in most cases, and I speculate that thrusting on a great scale has not decoupled most upper crustal terranes from their original substrate of lower crust.

On the other hand, some tectonostratigraphic terranes overlie lower crust of different character. For example, the Angayucham terrane is oceanic in character, but part of it lies along the northwestern flank of the Ruby geanticline, in which old cratonic rocks are exposed. An isolated granite body intrudes the Angayuchum terrane near the Ray Mountains, and has a high SIR, indicating the presence of cratonic rocks below the Angayucham rocks. Statewide, however, the surface area occupied by upper crustal terranes that are different from their basement appears to be quite small.

Finally, I note that many proposed tectonostratigraphic terranes have neighbors of similar type (cratonic, volcanic, or sedimentary), and these form coherent belts. These belts overlie large areas of basement that appear to be of matching type (Cratonia, Volcania, or Detritia). Thus, there may be much more genetic coherence in Alaskan crust than is implied by the myriad of proposed tectonostratigraphic terranes.

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