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# GEOCHEMISTRY AND PETROGRAPHY OF BASALTS RECOVERED FROM THE CONTINENTAL SLOPE IN THE EASTERN GULF OF ALASKA

By

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# Geochemistry and petrography of basalts recovered from the continental slope in the eastern Gulf of Alaska

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## Abstract

Basaltic rocks were dredged from the continental slope adjacent to the Yakutat shelf between long 138°00' W. and 142°30' W. in the eastern Gulf of Alaska. The early to middle Eocene basalts exhibit textures and primary mineralogy commonly found in ocean-floor basalt. Most samples are moderately to severely altered with secondary minerals typical of zeolite facies metamorphism. Major element chemistry is highly variable, and due to the addition of secondary alkalies, appears alkalic. Analyses of clinopyroxenes, which are usually the only unaltered primary mineral, indicate that these rocks are predominantly tholeiitic. Trace element chemistry indicates that these basalts are a heterogeneous group composed of anomalous, LILE-enriched (Type II) MORB and lesser amounts of normal, LILE-depleted (Type I) MORB. Similar assemblages of chemically diverse basalts of LILE-enriched and LILE-depleted tholeiites have been reported from seamounts on and near midoceanic ridges.

## Introduction

Bedrock outcrops along the continental slope adjacent to the Yakutat shelf were sampled in 1977, 1978, and 1979 as part of the U.S. Geological Survey program for evaluation of the geologic framework and petroleum potential of the outer continental shelf (OCS) in the Eastern Gulf of Alaska. Sedimentary and igneous rock, ranging from Cretaceous to Tertiary in age, were dredged from 40 sites along the 250-km-long northwest-trending continental slope between long 138°00' W. and 142°30' W. from water depths of 3,150 m to 200 m. The stratigraphy inferred from these samples, combined with the seismic reflection data, is described by Plafker and others (1980).

This paper presents petrologic and geochemical data for the basaltic rocks that comprise much of the lower continental slope throughout this area.

## Geologic setting

The segment of the continental slope sampled in this study is part of a relatively small triangular crustal plate that has been informally named the Yakutat block (Plafker and others, 1978b; Rodgers, 1978). Available earthquake, geologic, and marine seismic data suggest that most of the approximately 5.8 cm/yr relative motion between the Pacific and North American plates is presently being taken up along the Fairweather transform fault and Pamplona zone of thrust faults and folds. Relative motion between the Pacific plate and Yakutat block is small--perhaps on the order of 0.4 cm/yr (Lahr and Plafker, in press) and occurs mainly on a system of inferred faults (the Transition fault zone) at or near the base of the continental slope. Offshore parts of the Yakutat block are characterized by an asymmetric, deep shelf basin containing middle(?) and late Cenozoic sedimentary rocks, and a general absence of compressional deformation in the post-Paleocene Cenozoic section (Plafker and others, 1978a; Bruns, 1979). These features suggest that the

Yakutat continental slope has been a trailing or strike-slip margin--rather than a zone of convergence--throughout much of the Cenozoic. In this respect, the continental shelf and slope of the Yakutat block differ strikingly from the Yakataga area to the northwest where seaward-verging thrust faults and folds reflect pervasive late Cenozoic compression due to high rates of underthrusting along the Aleutian Trench and Pamplona zone.

The basaltic rocks recovered from the continental slopes between long 138°00' W. and 142°30' W. are part of a sequence inferred from seismic profiles to be at least 1,300 m in thickness. This sequence is composed of flows, showing some pillow structures, possibly including minor dikes and sills, pyroclastics, and minor interbedded sedimentary rocks. The unit is probably early to middle Eocene in age based on microfossils in interbedded shale and several basalt whole rock minimum K/Ar ages (Plafker and others, 1980).

## Methods

The samples used in this study were recovered during three cruises of the U.S. Geological Survey R/V Sea Sounder. Figure 1 shows the location of the dredge hauls. The samples were collected with a Benthos chain-bag dredge. Sampling method is decribed in detail by Plafker and others (1980).

Detailed petrographic studies, supported by X-ray diffraction analyses, were performed on 19 of the least-altered basalt samples.

Chemical analyses were performed in the analytical laboratories of the U.S. Geological Survey using X-ray fluorescence spectroscopy (XRF), direct reading emission spectroscopy, instrumental neutron activation analyses (INAA), and wet chemical methods. The nine major oxides $SiO_2$, $Al_2O_3$, $TiO_2$, MnO, MgO, CaO, $Na_2O$, $K_2O$, $P_2O_5$ and total iron as $Fe_2O_3$ were determined by XRF with an accuracy of 0.4 to 1.0 percent and precision of 1 to 2 percent. Ferrous iron, $H_2O$ and $CO_2$ were determined by wet chemical methods. XRF methods were used to analyze Ba, Rb, Sr, Zr, and Y in 11, and Nb in all, of the 19 samples with an accuracy of 5 to 10 percent and precision of 2 to 10 percent. The same 11 samples were analyzed for Cr, Ni, and Sc by direct reader emission spectroscopy with an accuracy of 10 to 15 percent and precision of 10 to 30 percent. Hf, Ta, Th, and the rare earth elements were determined in all 19 basalt samples by INAA with an accuracy of 5 to 20 percent and precision of 10 to 20 percent.

In addition to the whole rock chemistry, mineral chemistry of clinopyroxene in eight samples was determined with an ARL electron microprobe using an accelerating voltage of 15 kv, a sample current of 0.04 μA, and a beam diameter of 1 to 2 μm.

## Petrography

The basaltic rocks consist of a wide range of textural types. Petrographic data and modal mineralogies of the 19 analyzed basalt samples are summarized in Table 1.

Most samples are massive to sparsely amygdaloidal but two samples have more than 20 percent amygdules by volume. Observed textures include hyalopilitic, variolitic, intergranular, intersertal, and ophitic. Some of the basalts are aphyric but most are sparsely phyric (<10 percent) and a few are moderately phyric (10-15 percent). The phenocryst minerals are predominantly plagioclase, which is usually accompanied by lesser amounts of pyroxene and only rarely by olivine. The primary plagioclase phenocrysts range from 0.5 to 5.0 mm in size and are calcic labradorite in composition. Typically, the plagioclase phenocrysts are severely altered to zeolites, clays, and in some cases to K-feldspar and albite. The pyroxene phenocrysts usually are smaller in size (<2 mm) and are partly or completely replaced by chlorite, chlorophaeite, and (or) a smectite clay. When not altered, the pyroxene phenocrysts are sector-zoned augite. The olivine phenocrysts are typically small (<1 mm) pseudomorphs of smectite(?) with iddingsite alteration rims. The groundmass phases are plagioclase, clinopyroxene, opaques, altered glass, and, in two samples, minor olivine. The groundmass plagioclase, like the phenocrysts, are usually altered to clays and zeolites, but when fresh appear to be mostly Ca-poor labradorite and minor andesine in composition. Clinopyroxene is clear to pale-brown augite and is typically unaltered, even in highly altered samples. Opaques are mostly titanomagnetite, often rimmed and stained by iron oxides. Euhedral pyrite is abundant in some samples. A large variety of other secondary minerals, including clays, chlorite (chlorophaeite), zeolites, calcite, epidote, and secondary feldspars, are present as mineral and glass replacement or as veinlet and amygdule filling. A variety of zeolites, including analcime, are present, but most have been identified by X-ray diffraction and broad beam microprobe analysis as natrolite and phillipsite.

## Major element chemistry

The major element composition and normative mineralogy for 19 basalt samples are shown in Table 2. The samples are variable in $SiO_2$ ranging from 47.2 to 51.8 percent. $Al_2O_3$ is moderate to high ranging from 13.0 to 18.1 percent. MgO concentrations are typically around 7 percent but range from 5.9 to 9.7 percent, showing no well defined trend with other oxides, modal, or normative olivine abundances. CaO concentration ranges from 6.7 to 12.2 percent, and alkalies are even more variable with $Na_2O$ ranging from 2.8 to 5.6 percent and $K_2O$ from 0.08 to 1.7 percent. $Na_2O$ content correlates positively with abundance of zeolites, but high $K_2O$ content can only sometimes be explained by the presence of phillipsite and secondary K-feldspar. $TiO_2$ concentrations are usually moderately high, around 1.5 to 2 percent, but two samples have less than 1 percent. $P_2O_5$ and MnO are generally low, ranging from 0.08 to 0.39 percent and from 0.06 to 0.28 percent, respectively.

The major element chemistry suggests that most of these basalts are alkalic. All except three samples plot in the alkaline field on an alkalies vs. silica diagram (MacDonald and Katsura, 1964). Clearly the large alkali content and the large variation in composition of some other oxides are the result of secondary alteration. The $H_2O$ content is extremely high, ranging from 2.9 to 7.6 percent; $CO_2$ ranges from 0.01 to 4.2 percent, and the $Fe_2O_3$/FeO ratio is highly variable ranging from 0.23 to 3.45. The $H_2O$ content correlates positively with $Na_2O$ concentration but no equally well defined trend is apparent for $K_2O$ or $Fe_2O_3$/FeO vs. $H_2O$.

The normative mineral composition is also easily affected by secondary alteration. Eleven of the 19 samples are nepheline normative, reflecting the high secondary alkali concentrations. Six samples are olivine-hypersthene normative, and two are quartz normative.

## Trace element chemistry

The result of analyses for 19 trace elements in individual samples are summarized in Table 3. Not every basalt sample was analyzed for all 19 trace elements, nor was the same method of analysis used for all samples.

The abundance of LIL (large ion lithophile) elements is a more sensitive indicator of basalt petrogenesis than major element abundances. Unfortunately, large cations of low valency, such as Ba, Rb, Sr, are also very susceptible to secondary alteration. The Ba, Rb, and Sr concentrations in the basalt samples are highly variable, ranging for Ba from 20 to 264 ppm, for Rb from 5 to 15 ppm, and for Sr from 97 to 353 ppm. Ba, Rb, and Sr abundances correlate positively with K but no equally well defined trend exists relative to Na and Ca. K/Ba and K/Rb ratios are also highly variable but Sr/Rb ratios are low and less variable.

High valency LIL elements like Zr, Hf, Nb, Ta, and Th are also incompatible and consequentially not appreciably incorporated in common minerals, but, unlike Ba, Rb, and Sr, not as mobile during secondary alteration processes (Winchester and Floyd, 1976, 1977). Concentrations of Zr (57-194 ppm), Hf (1.8-4.4 ppm), Nb (<5 to 15 ppm), Ta (0.3-1.2 ppm), and Th (0.3-1.0 ppm) are too low for normal alkalic basalts and show greater similarity to oceanic tholeiites.

The compatible elements Cr, Ni, and Sc are typically incorporated into ferromagnesian minerals. Cr and Ni are moderately high, generally over 100-200 ppm and 60 to 130 ppm, respectively, but one sample (22A8) is abnormally depleted in Cr (34 ppm) and Ni (22 ppm). Sc shows a narrower range from 29 to 47 ppm. High Cr and Ni concentrations show a rough correlation with high Mg values.

The concentrations of rare earth elements in the 19 samples is included in Table 3. A summary of the chondrite normalized REE distribution is shown in Figure 2. All show some LREE over HREE enrichment with La/Yb ranging from 1.05 to 5.36. The greatest LREE over HREE enrichment is observed in the quartz-normative tholeiite 22A7. Eight samples have $La_N/Sm_N$ ratios of less than 1.0 and their average and range in composition are shown in Fig. 2. Likewise, the 11 samples with $La_N/Sm_N > 1$ are averaged and their range shown as a field. It is interesting to note that the abundance of HREE for both groups is almost identical, while the fields of LREE show almost no overlap.

## Clinopyroxene chemistry

In highly altered basalt, clinopyroxene crystals are frequently the only unaltered phase of the original rock. The existence of broad correlations between clinopyroxene composition and host lava chemistry has been established many years ago (Kushiro, 1960; LeBas, 1962; Coombs, 1963). The clinopyroxenes of tholeiites are typically poorer in Al, Na, and Ti, but richer in Si and Cr than clinopyroxenes from alkali basalts. The origin of these correlations is complex and not well understood. Besides bulk composition of the magma and crystallization sequence, which is controlled by pressure and oxygen fugacity, the cooling rate can also affect pyroxene chemistry (Barberi and others, 1971; Coish and Taylor, 1979).

Representative clinopyroxene analyses for eight basalt samples are shown in Table 4. In seven samples the analyzed clinopyroxenes are groundmass crystals; in one sample (33H) the analysis is of a microphenocryst which represents the only unaltered phase. The microprobe analysis reports total iron as FeO; the ferric iron content was estimated by using the method of Papike and others (1974).

The clinopyroxenes in the dredged basalt samples show a narrow compositional range with high $SiO_2$ (>50 percent), typically low $Al_2O_3$ ( 2.5 to 3.0 percent), low $TiO_2$ (<1 percent), and low $Na_2O$ ($\sim$0.3 percent). $Cr_2O_3$ is much more variable, ranging from 0.03 to 0.6 percent. The basalt samples appear typically tholeiitic although some grains are a little higher in $Al_2O_3$ (up to 4 percent) and CaO (21 percent). Ti and Al content increase in clinopyroxene with increasing cooling rate; hence, a clinopyroxene from a chilled margin can be higher in Ti and Al than one from the interior region of the same rock. Cr content is often highly variable in clinopyroxene crystals in the same rock since it is concentrated in the crystals first to crystallize. The clinopyroxene composition of eight of the dredged basalt samples is shown on a Ca-Mg-Fe diagram (Fig. 3). On $SiO_2$ vs. $Al_2O_3$ (Fig. 4) and $Al^{IV}$ vs. $TiO_2$ variation diagrams (LeBas, 1962) the pyroxenes plot in the tholeiite field.

## Discussion

### Petrography and alteration

The basalt samples dredged from the continental slope of the Yakutat block exhibit a spectrum of textures and primary mineralogy commonly found in ocean-floor basalts. All samples are at least somewhat altered; some are severely altered. The presence of Na-zeolites in altered ocean-floor basalt is a common occurrence; the presence of potash feldspar is rare but has been reported by Jehl and others (1976) in rocks from the North Atlantic and by Liou (1979) in an ophiolite suite from Taiwan. Authigenic potash feldspar commonly forms in geothermal fields but is rare in $K_2O$ depleted host rock such as ocean-floor basalt. The presence of secondary potash feldspar in some of the dredged samples suggests that some of these rocks have been subjected to local metasomatic exchange with a K-rich hydrothermal solution under zeolite facies pressure and temperature conditions (Hemley, 1959). The bulk of the secondary minerals, such as natrolite, phillipsite, calcite, and smectites, crystallize under a wide range of temperatures but are typically considered to be the result of submarine weathering (Baragar and others, 1976; Bohlke and others, 1980). No unequivocally metamorphic zeolites, such as laumontite or wairakite, have been found in these samples.

### Major element chemistry

The basalts from the Yakutat block show great chemical diversity. On the basis of normative composition, some are quartz tholeiites, some olivine tholeiites, but most are olivine alkali basalts. The addition of large amounts of secondary alkalies can make a tholeiitic rock appear alkalic. The nepheline-normative composition of most of these rocks is clearly the result of alkali enrichment by secondary alteration. Other major oxides, although not as susceptile to alteration as the alkalies, are also affected to varying degrees. The FeO*/MgO ratio, which is typically less sensitive to alteration, is probably affected by the addition of pyrite and the removal or addition of Mg. $K_2O$ in combination with $TiO_2$, $SiO_2$, and MgO provides the most effective major element discriminant of ocean floor from other types of basalts. Unfortunately, even the samples with low $K_2O$ (<0.3 percent) have very high $H_2O$, $Na_2O$, $CO_2$ or $Fe_2O_3$/FeO. Clearly, major element chemistry is of limited use in inferring the petrotectonic affinities of these basalts.

### Trace element chemistry

The trace element abundances in the basalts dredged from the Yakutat block also show considerable diversity. Large, low valency cations like Ba, Rb, and Sr are most variable showing considerable enrichment over normal oceanic tholeiite but are not enriched enough for typical alkalic basalt. Since Ba, Rb, and Sr are susceptible to sea-water alteration like K, it is conceivable that they followed the same enrichment trend and their ratio to K may have been preserved. The K/Ba ($\sim$100) and K/Rb ($\sim$800-900) ratios observed in several samples are very high and similar to that in normal ocean ridge basalt. The large high valency cations, are better indicators of basalt origin because they are relatively immobile during alteration. These elements have been widely used to discriminate among basalts from different tectonic settings (Pearce and Cann, 1973; Winchester and Floyd, 1975, 1977; Wood, 1980). Eleven of the dredged basalt samples are shown on a $TiO_2$ vs. Y/Nb diagram (Fig. 5) and all samples are shown on a Th-Hf-Ta diagram (Fig. 6). On the $TiO_2$ vs. Y/Nb plot most samples plot in the field of ocean-floor tholeiite but two samples plot in the field of ocean-island tholeiite. On the Th-Hf-Ta diagram six samples plot in the field of normal (N-type) MORB; all others plot in the enriched (E-type) MORB and within-plate tholeiite which cannot be distinguished on the basis of these elements. Normal MORB or Type I ocean floor of Bryan et al. (1976) is the low K, LREE depleted abyssal tholeiite described by Engel et al. (1965) and Kay et al. (1970) that is erupted along the normal segments of midoceanic ridges. Type II basalt, or E-type MORB, which is erupted near islands or platforms astride midocean ridges, is indistinguishable petrographically from Type I basalt but has distinctive, enriched trace element compositions. However, Type II ocean-floor basalt has trace element compositions very similar to ocean-island tholeiite that is erupted within plates as the result of plume or "hot spots" within the mantle (Basaltic Volcanism Project, 1981).

The variable, but generally high, concentrations of Cr, Ni, and Sc are indicative of subalkalic composition but are not able to distinguish between Type II MORB and ocean-island tholeiite.

### REE chemistry

Normal MORB is characterized by LREE depletion showing typically a concave downward chondrite normalized REE pattern. Eight of the basalts show an overall concave pattern with $La_N/Sm_N$ <1.0, but La and Ce appear to have been selectively mobilized. It has been shown that REE can also be mobilized by alteration processes; especially LREE like La can be selectively enriched over HREE (Hellman et al., 1976; Ludden and Thompson, 1979). The remaining samples have LREE-enriched patterns characteristic of E-type MORB and oceanic-island basalt. The REE distribution in the basalts dredged from the "Yakutat block" are very similar to those in basalts dredged from young seamounts near the East Pacific Rise (EPR) (Batiza, 1980; Batiza and Vanko, 1983), and both are shown in Figure 7 along with typical patterns of N-type and E-type MORB.

### Clinopyroxene composition

The clinopyroxene chemistry confirms what the trace element data indicate--that, indeed, these rocks are predominantly tholeiitic and not alkalic. The clinopyroxene composition of the basalts dredged from the Yakutat block is similar to those in basalts from DSDP sites in the Atlantic and Pacific Ocean (Mazzullo and Bence, 1976; Ayuso et al., 1976), and similar to the most commonly observed clinopyroxene composition in ocean-floor basalt of $Wo_{30-40}En_{50}Fs_{10-15}$. Hawaiian tholeiite clinopyroxene is typically a little richer in Ti and Ca but there is considerable overlap in compositions (Basaltic Volcanism Project, 1981).

## Conclusions

The basalts dredged from the continental slope in the Yakutat block are predominantly tholeiitic, although secondary alkali enrichment makes them appear alkalic. Textures and primary mineralogy are typical of ocean-floor basalt formed at diverging plate margins. Clinopyroxene chemistry confirms the tholeiitic nature of most of these samples, and shows similarity to typical clinopyroxene compositions of ocean-floor and oceanic island basalts. Trace element data indicate that these basalts represent mostly anomalous, LILE-enriched, Type II MORB with lesser amounts of normal, LILE-depleted, Type I MORB. The enriched Type II MORB has trace element affinities with ocean-island tholeiites that are erupted in an intraplate setting, presumably as the result of plume or "hot spot" activity in the mantle. The occurrence of LILE-enriched, Type II basalts in a spreading environment have been explained as "plume-related" geochemical variations even where there is no evidence of structural or bathymetric anomalies associated with a "plume" (Schilling and others, 1983). A similar group of chemically diverse rocks have been dredged from small seamounts near the East Pacific Rise consisting mostly of depleted N-MORB and lesser volumes of enriched transitional and even alkalic lavas erupted from the same volcano. The enriched lavas are more likely to be found on relatively older lithosphere (Batiza, 1980; Batiza and Vanko, 1983).

We suggest that basalts of the "Yakutat block" may have formed in a similar environment in the Eocene, erupting LILE-depleted lavas near the spreading center and LILE-enriched transitional lavas with increasing distance from the ridge.

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## References cited

Ayuso, R. A., and Bence, A. E., 1976, Upper Jurassic tholeiitic basalts from DSDP Leg 11: Journal of Geophysical Research, v. 81, p. 4305-4325.

Baragar, W. R. A., Plant, A. G., Pringle, G. J., and Schau, Mikkel, 1976, Petrology and alteration of selected units of Mid-Atlantic Ridge basalts sampled from sites 332 and 335, DSP: Canadian Journal of Earth Sciences, v. 14, p. 837-874.

Barberi, F., Bizouard, H., and Varet, J., 1971, Nature of the clinopyroxene and iron enrichment in alkalic and transitional basaltic magmas: Contributions to Mineralogy and Petrology, v. 33, p. 93-107.

Basaltic Volcanism Project, 1981, Basaltic volcanism on the terrestrial planets: Pergamon Press, New York, 1286 p.

Batiza, R., 1980, Origin and petrology of young oceanic central volcanoes: Are most tholeiitic rather than alkalic?: Geology, v. 8, p. 477-482.

Batiza, R., and Vanko, D., 1983, Petrology of young Pacific seamounts: Journal of Geophysical Research (in press).

Bohlke, J. K., Honnorez, J., and Honnorez-Guerstein, B. M., 1980, Alteration of basalts from site 396B, DSDP: Petrographic and mineralogic studies: Contributions to Mineralogy and Petrology, v. 73, p. 341-364.

Bruns, T. R., 1979, Late Cenozoic structure of the continental margin, northern Gulf of Alaska, in Sisson, Alexander, ed., 1979, The relationship of plate tectonics to Alaskan geology and resources: Proceedings, Sixth Alaska Geological Society Symposium, Anchorage, 1977, p. I1-I30.

Bryan, W. B., Thompson, G., Frey, F. A., and Dickey, J. S., 1976, Inferred geologic settings and differentiation in basalts from the Deep-Sea Drilling Project: Journal of Geophysical Research, v. 81, p. 4285-4304.

Coish, R. A., and Taylor, L. A., 1979, The effects of cooling rate on texture and pyroxene chemistry in DSDP Leg 34 basalt: A microprobe study: Earth and Planetary Science Letters, v. 42, p. 389-398.

Coombs, D. S., 1963, Trends and affinities of basaltic magmas and pyroxenes as illustrated on the diopside-olivine-silica diagram: Mineralogical Society of America, Special Paper 1, p. 227-250.

Engel, A. E., Engel, C. G., and Havens, R. G., 1965, Chemical characteristics of oceanic basalts and the upper mantle: Geological Society of America Bulletin, v. 76, p. 719-734.

Hellman, P. L., Smith, R. W., and Henderson, P., 1979, The mobility of the rare earth elements: Evidence and implications from selected terrains affected by burial metamorphism: Contributions to Mineralogy and Petrology, v. 71, p. 23-44.

Hemley, J. J., 1959, Some mineralogical equilibria in the system $K_2O-Al_2O_3-H_2O$: American Journal of Science, v. 257, p. 241-270.

Jehl, V., Poty, B., and Weisbrod, A., 1976, Hydrothermal metamorphism of the oceanic crust in the north Atlantic Ocean abs. : EOS (Transactions of American Geophysical Union), v. 57, p. 597-598.

Kay, R. N., Hubbard, N. J., and Gast, P. W., 1970, Chemical characteristics and orgin of oceanic ridge volcanic rocks: Journal of Geophysical Research, v. 75, p. 1585-1613.

Kushiro, I., 1960, Si-Al relation in clinopyroxene from igneous rocks: American Journal of Science, v. 258, p. 548-554.

Lahr, J. C., and Plafker, George, 1980, Holocene Pacific-North American plate interaction in southern Alaska: implications for the Yakataga seismic gap: Geology, .

LeBas, M. J., 1962, The role of aluminum in igneous clinopyroxenes with relation to their parentage: American Journal of Science, v. 260, p. 267-288.

Liou, J. G., 1979, Zeolite facies metamorphism of basaltic rocks from the East Taiwan ophiolite: American Mineralogist, v. 64, p. 1-14.

Ludden, J. N., and Thompson, G., 1979, An evaluation of the behavior of the rare earth elements during the weathering of sea-floor basalt: Earth and Planetary Science Letters, v. 43, p. 85-92.

MacDonald, G. A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, p. 82-133.

Mazzullo, L. J., and Bence, A. E., 1976, Abyssal tholeiites from DSDP Leg 34: The Nazca Plate: Journal of Geophysical Research, v. 81, p. 4327-4351.

Papike, J. J., Cameron, K. L., and Baldwin, K., 1974, Amphiboles and pyroxenes: characterization of other than quadrilateral components and estimates of ferric iron from microprobe data: Geological Society of America Abstracts with Programs, v. 6, p. 1053-1054.

Papike, J. J., and White, C., 1979, Pyroxenes from the planetary basalts: characterization of "other" than quadrilateral components: Geophysical Research Letters, v. 6, p. 913-916.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290-300.

Plafker, George, Bruns, T. R., Carlson, P. R., Molnia, B. F., Scott, E. W., Kahler, Roger, and Wilson, Charles, 1978a, Petroleum potential, geologic hazards, and technology for exploration in the outer continental shelf of the Gulf of Alaska Tertiary province: U.S. Geological Survey Open-File Report 78-490, 33 p.

Plafker, George, Hudson, Travis, Rubin, Meyer, and Bruns, T. R., 1978b, Late Quaternary offsets along the Fairweather fault and crustal plate interactions in southern Alaska: Canadian Journal of Earth Sciences, v. 15, p. 805-816.

Plafker, George, Winkler, G. R., Coonrad, W. L., and Claypool, George, 1980, Preliminary report on the geology of the continental slope adjacent to OCS Lease Sale 55, Eastern Gulf of Alaska: Petroleum resource implications: U.S. Geological Survey Open-File Report 80-1089, 72 p.

Rodgers, J. F., 1977, Implications of plate tectonics for offshore Gulf of Alaska petroleum exploration: Proceedings, 9th Annual Offshore Technology Conference, p. 11-16.

Schilling, J. G., Zagac, M., Evans, R., Johnston, T., White, W., Devine, J. D., and Kingsley, R., 1983, Petrologic and geochemical variations along the mid-Atlantic ridge from 29°N to 73°N: American Journal of Science, v. 282, p. 510-586.

Winchester, J. A., and Floyd, P. A., 1976, Geochemical magma type discrimination: Application to altered and metamorphosed basic igneous rocks: Earth and Planetary Science Letters, v. 28, p. 459-469.

_____1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325-343.

Wood, D. A., 1980, The application of a Th-Hf-Ta diagrams to problems of tectonomagmatic classification and to establishing the nature of crystal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, p. 11-30.

## Illustrations

Figure 1. Map showing locations of dredged outcrop samples.
Figure 2. Chondrite normalized REE data for dredged basalt samples.
Figure 3. Pyroxene data for dredged basalts plotted on Ca-Mg-Fe (atomic) ternary diagram.
Figure 4. $SiO_2$-$Al_2O_3$ variations in pyroxenes from the dredge basalts.
Figure 5. $TiO_2$ vs. Y/Nb diagram.
Figure 6. Th-Hf/3-Ta diagram.
Figure 7. Chondrite normalized REE distributions in N-type and E-type MORB and in basalts dredged from seamounts near the East Pacific Rise shown for comparison with basalts from the Eastern Gulf of Alaska.

## Tables

Table 1. Modal mineralogy and petrography of dredged basalt samples.
Table 2. Major elements, major element volatile-free and normative mineral composition.
Table 3. Trace element abundances.
Table 4. Representative clinopyroxene compositions from dredged basalt samples.

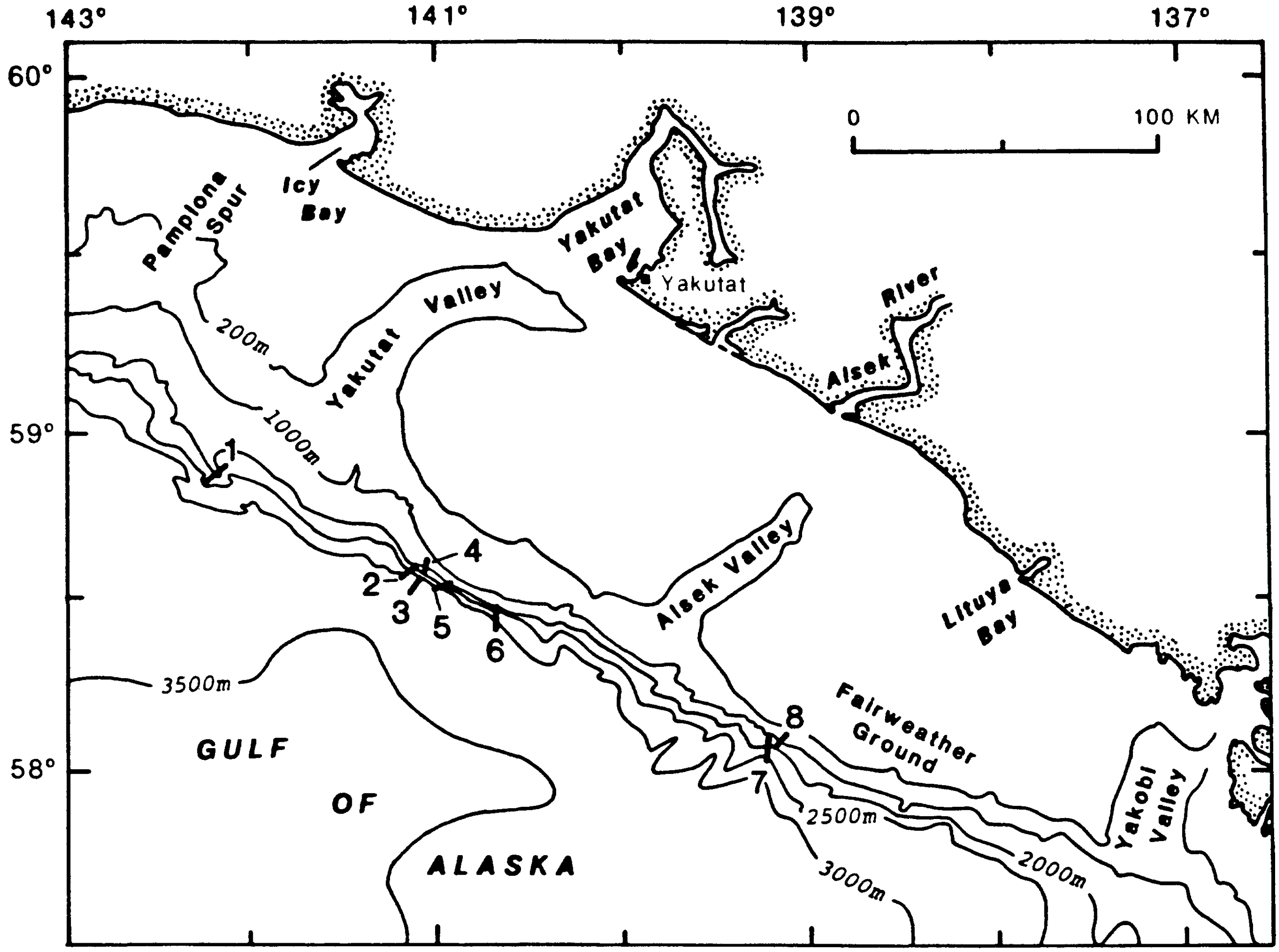

Figure 1. Map showing locations of dredged basalt samples described in text and tables.

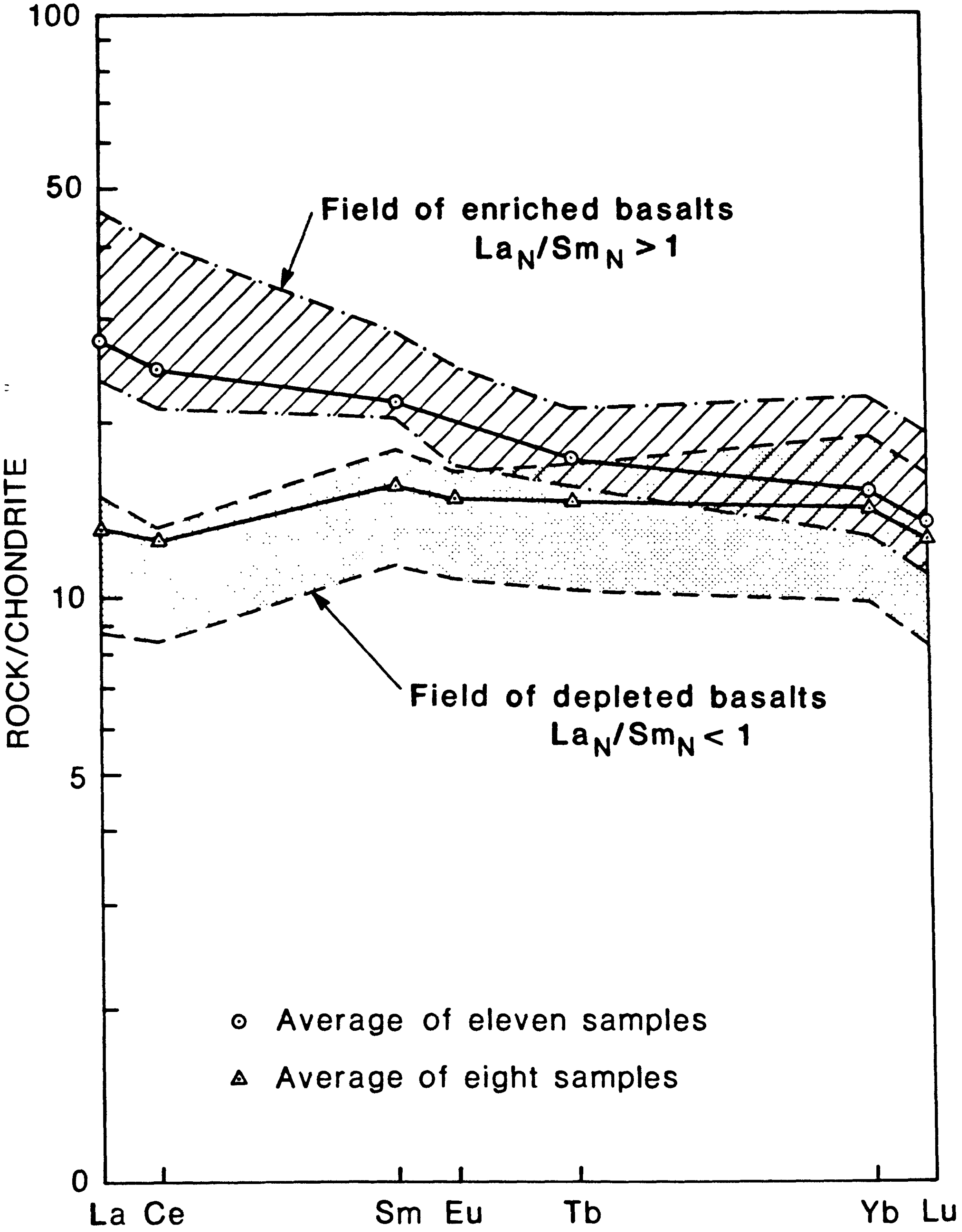

Figure 2. REE distribution for basalts dredged from the continental slope in the Eastern Gulf of Alaska normalized to average REE abundance in chondrites (Haskin et al.,1968). Note the similar abundance of heavy REE for both the LREE-depleted and enriched basalts.

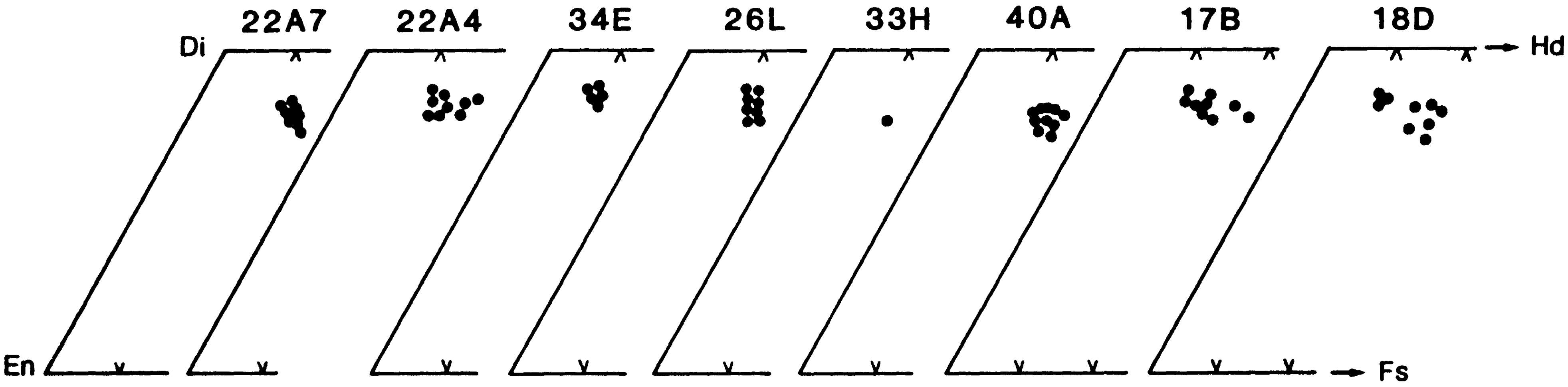

Figure 3. Pyroxene composition in terms of atomic Ca-Mg-ΣFe (ΣFe as FeO) for eight basalt samples dredged from the continental slope in the Eastern Gulf of Alaska.

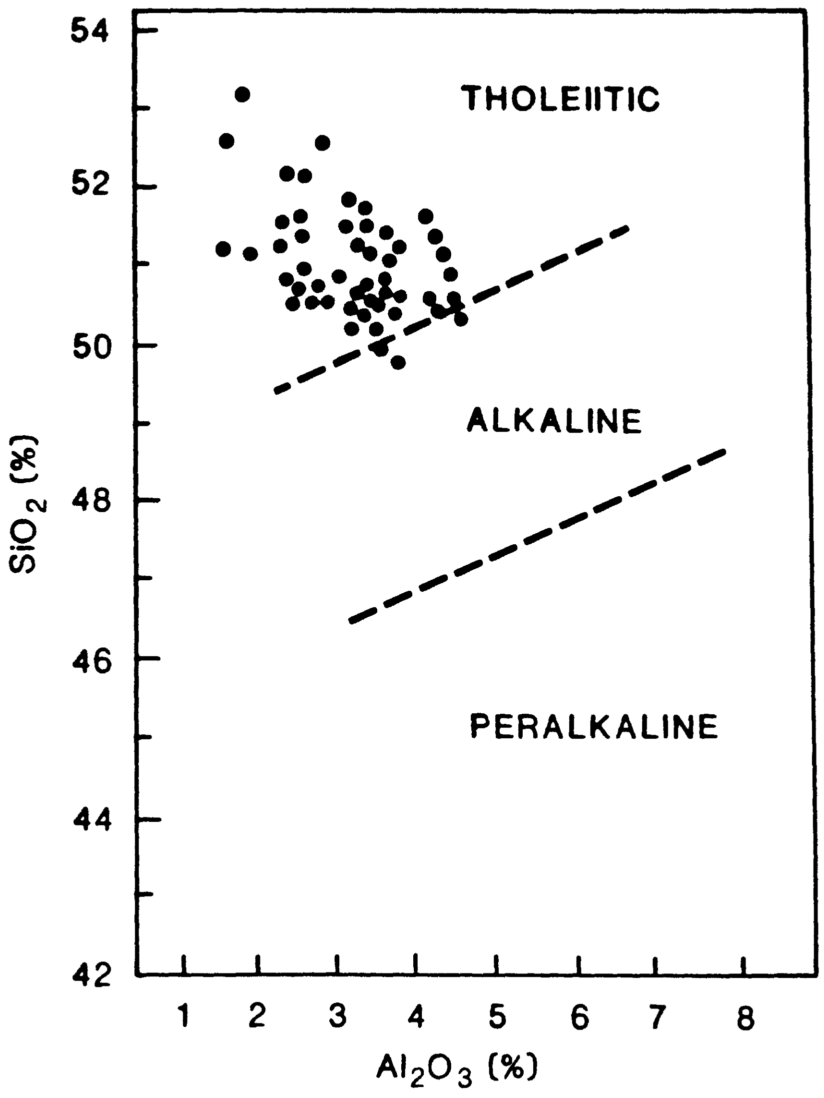

Figure 4. $SiO_2$ vs. $Al_2O_3$ variation in clinopyroxene in basalt dredged from the continental slope in the Eastern Gulf of Alaska (fields after LeBas, 1962).

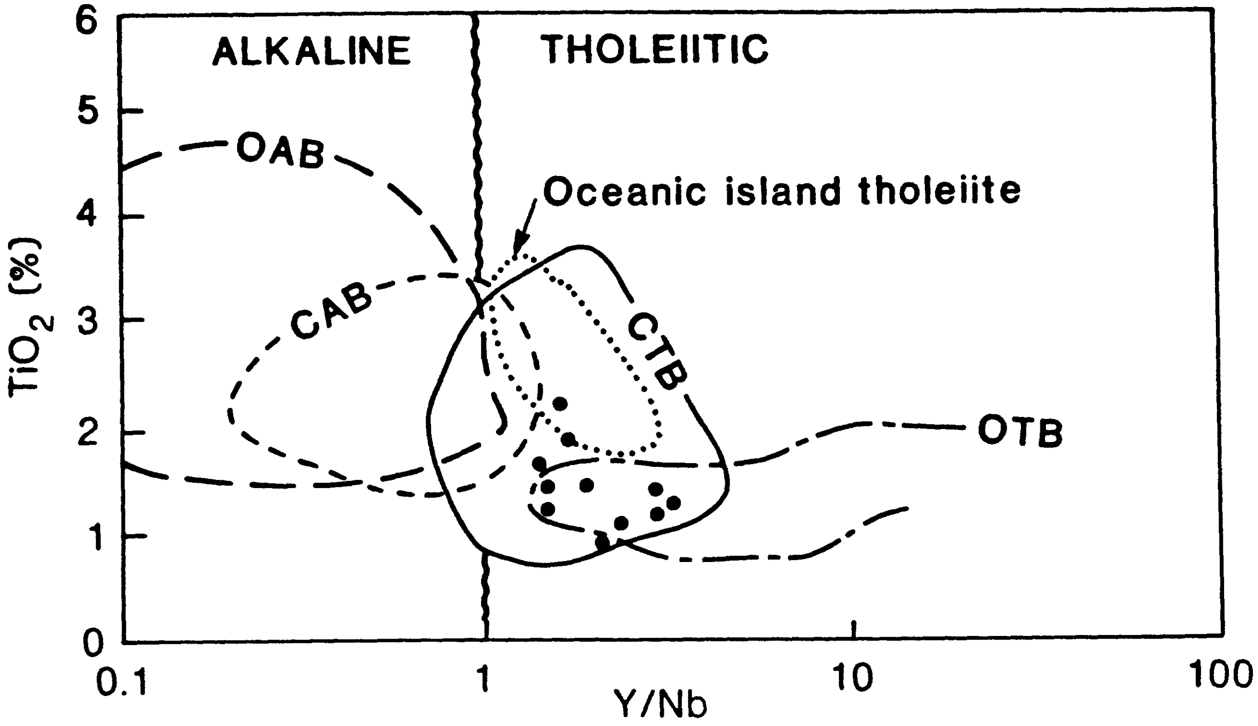

Figure 5. $TiO_2$ vs. Y/Nb diagram for the basalts from the continental slope in the Eastern Gulf of Alaska. Petrotectonic fields after Winchester and Floyd (1976). OTB= oceanic tholeiitic basalt, CTB= continental tholeiitic basalt,CAB= continental alkalic basalt, OAB= oceanic alkalic basalt.

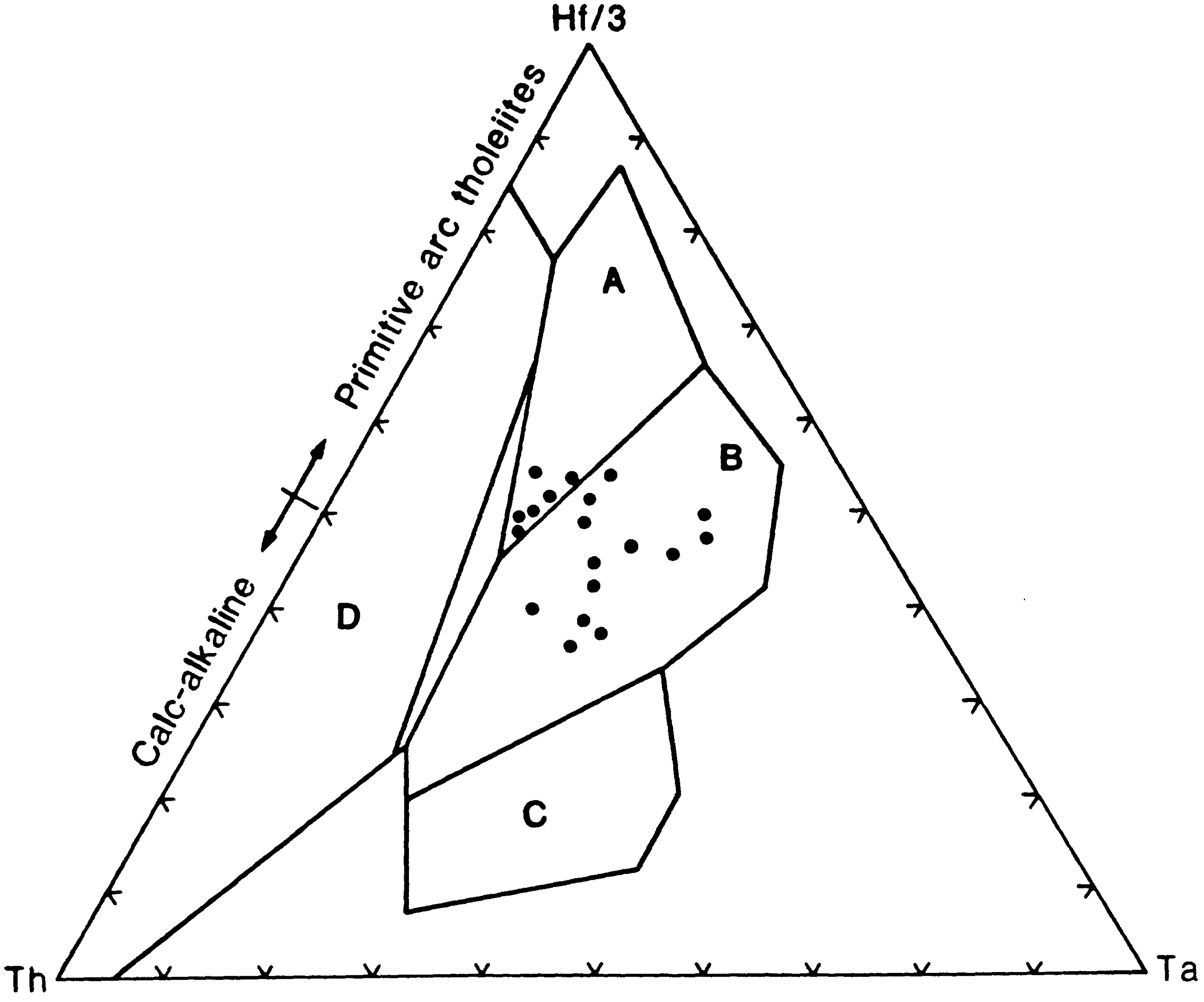

Figure 6. Hf-Th-Ta diagram for the basalts dredged from the continental slope in the Eastern Gulf of Alaska. Petrotectonic fields after Wood (1980). A= N-type MORB, B= E-type MORB and tholeiitic intraplate basalt, C= alkaline intraplate basalt, D= destructive plate margins.

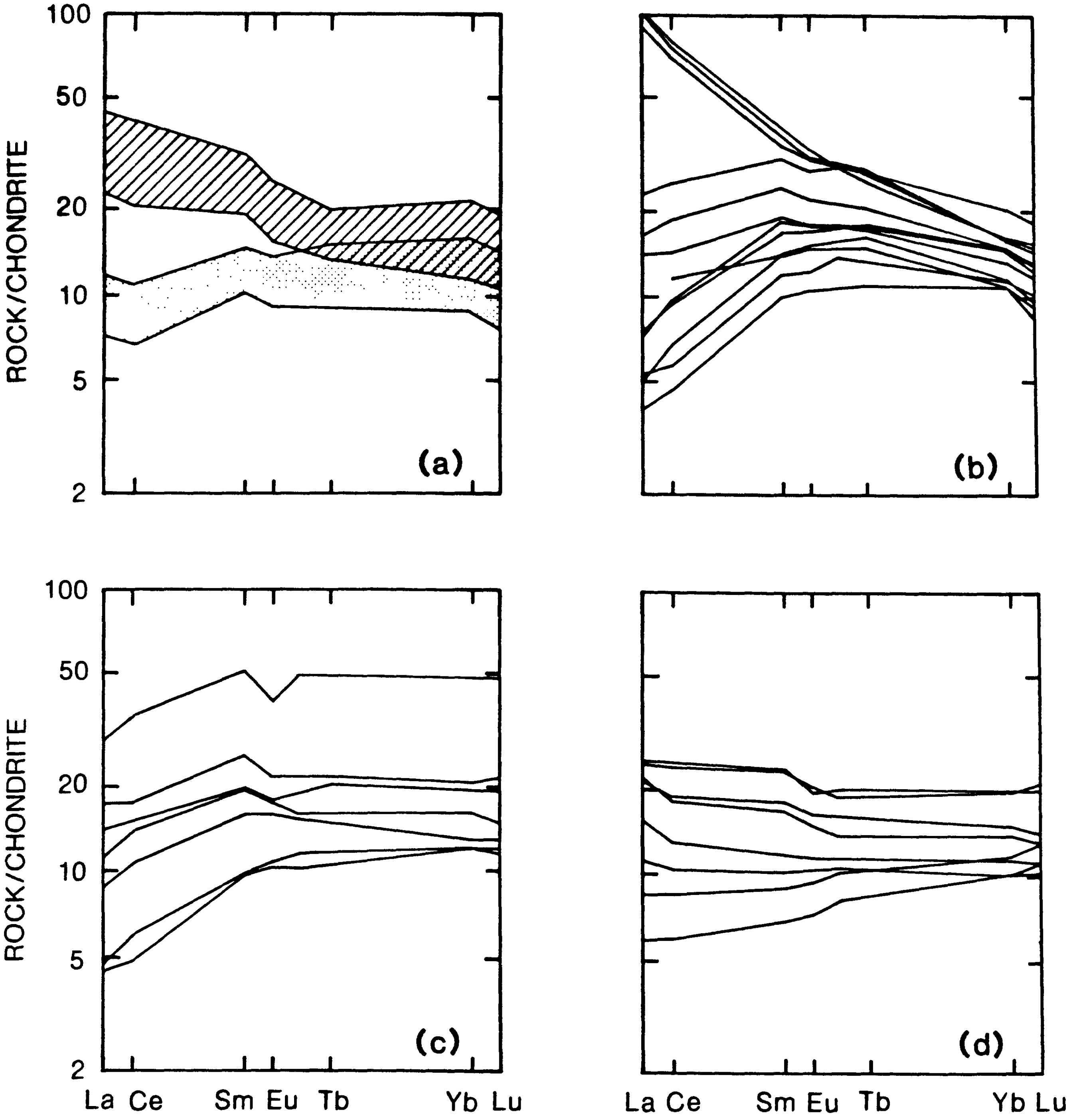

Figure 7. Chondrite-normalized REE distributions for basalts (a) from the continental slope in the Eastern Gulf of Alaska, (b) from seamounts near the East Pacific Rise (Batiza,1980),and (c) N-type MORB and (d) E-type MORB (Basaltic Volcanism Project,1980) for comparison.

Table 1. Petrography of basalts dredged from the continental slope in the eastern Gulf of Alaska

| Map No. (Fig. 1) | Sample Designation | Rock type | Texture | Mineralogy (estimated volume percent) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Amygdules | Phenocrysts | Groundmass | |
| | | | | | | Primary | Secondary |
| 1 | 78-22A3 | Basalt (highly altered) | Fine-grained, amygdaloidal, porphyritic, intersertal | 8%<br>Chlorite, calcite, clay minerals, albite | 5%<br>Plagioclase (altered to clay and K-feldspar<br>Pyroxene (altered to chlorite) | Plagioclase 25%<br>Opaques 5% | Chlorophaeite )<br>Chlorite ) 35%<br>Clay minerals 15%<br>Calcite 5%<br>Sphene 2% |
| 1 | 78-22A4 | Diabase (moderately altered) | Fine- to medium-grained, ophitic to intersertal | --- | --- | Plagioclase 40%<br>Clinopyroxene 30%<br>Opaques 10% | Chlorite )<br>Chlorophaeite ) 20% |
| 1 | 78-22A5 | Basalt (moderately altered) | Fine-grained, hyalopilitic to variolitic | --- | --- | Plagioclase 25%<br>Pyroxene 5%<br>Opaques 15%<br>Glass (devitrified) 35% | Epidote 10%<br>Chlorophaeite )<br>Chlorite ) 9%<br>Zeolites, )<br>Secondary feldspar) 1% |
| 1 | 78-22A7 | Basalt (very slightly altered) | Fine- to medium-grained, intergranular, to intersertal | --- | --- | Plagioclase 50%<br>Clinopyroxene 25%<br>Opaques 12% | Chlorite )<br>Chlorophaeite ) 13% |
| 1 | 78-22A8 | Basalt (highly altered) | Very fine grained, amygdaloidal, intergranular to intersertal | 5%<br>Calcite, chlorite, albite, clay, and zeolites | --- | Plagioclase 25%<br>Opaques 25% | Chlorite )<br>Chlorophaeite ) 20%<br>Calcite, zeolites)<br>Feldspar, silica ) 15%<br>Clay minerals 7%<br>Sphene 3% |
| 2 | 79-40A | Olivine-bearing basalt (moderately altered) | Fine-grained, amygdaloidal, intergranular to intersertal | 20%<br>Zeolites, chlorite | --- | Plagioclase 30%<br>Clinopyroxene 20%<br>Olivine(?) 5%<br>Opaques 13% | Chlorite )<br>Chlorophaeite ) 12% |
| 3 | 79-33G | Basalt (moderately altered) | Very fine grained, amygdaloidal, porphyritic, hyalopilitic to intersertal | 3%<br>Zeolites, calcite, clay minerals, chlorite | 2%<br>Plagioclase (altered to zeolites)<br>Clinopyroxene (altered to chlorophaeite) | Plagioclase 25%<br>Clinopyroxene 15%<br>Olivine(?) Tr<br>Opaques 20%<br>Devitrified glass 28% | Chlorophaeite )<br>Chlorite ) 5%<br>Zeolites 2% |
| 3 | 79-33H | Basalt (moderately altered) | Very fine grained, porphyritic, intergranular to intersertal | --- | 2%<br>Plagioclase (altered to zeolites)<br>Pyroxene (altered to chlorophaeite) | Plagioclase 40%<br>Clinopyroxene 20%<br>Opaques 25% (mostly pyrite) | Chlorophaeite 13% |

Table 1. Description of basalts dredged from the continental slope in the eastern Gulf of Alaska (Continued)

| Map No. (Fig. 1) | Sample Designation | Rock type | Texture | Mineralogy (estimated volume percent) | | Groundmass | |
|---|---|---|---|---|---|---|---|
| | | | | Amygdules | Phenocrysts | Primary | Secondary |
| 4 | 79-34E | Basalt (moderately altered) | Very fine grained, amygdaloidal, porphyritic, intersertal | 5%<br>Chlorophaeite, chlorite, clay minerals | 5%<br>Plagioclase (altered to clay and K-feldspar)<br>Pyroxene (altered to chlorophaeite or smectite) | Plagioclase 35%<br>Clinopyroxene 25%<br>Opaques 15% | Chlorophaeite 13%<br>Zeolites 2% |
| 5 | 79-26F | Olivine-bearing basalt (moderately altered) | Very fine grained, amygdaloidal, glomeroporphyritic, intergranular to intersertal | 25%<br>Zeolites, chlorite, albite | 5%<br>Plagioclase (clay)<br>Pyroxene<br>Olivine with iddingsite rim (altered to smectite?) | Plagioclase 25%<br>Clinopyroxene 20%<br>Opaque 10%<br>Biotite Tr | Limonite )<br>Hematite ) 5%<br>Chlorophaeite 10% |
| 5 | 79-26K | Basalt (moderately altered) | Very fine grained, amygdaloidal, porphyritic, intersertal | 5%<br>Zeolites, chlorite, secondary feldspar | 15%<br>Plagioclase (altered to zeolites and clay)<br>Clinopyroxene (chloritized) | Plagioclase 20%<br>Clinopyroxene 25%<br>Opaques 8% | Chlorophaeite )<br>Chlorite ) 15%<br>Zeolites, feldspars ) 12% |
| 5 | 79-26L | Basalt (slightly altered) | Very fine grained, amygdaloidal porphyritic, intersertal | 2%<br>Chlorite<br>Zeolites | 5%<br>Plagioclase<br>Pyroxene (altered to smectite) | Plagioclase 35%<br>Clinopyroxene 32%<br>Opaques 10% | Chlorophaeite 15%<br>Zeolites 1% |
| 5 | 79-26I | Olivine basalt (highly altered | Fine-grained, amygdaloidal, porphyritic, intersertal | 25%<br>Radial crystals of zeolites, clay minerals, chlorite, K-feldspar, albite | 10%<br>Plagioclase (clay, zeolite alteration)<br>Pyroxene and olivine with iddingsite (both replaced by smectite) | Plagioclase 18%<br>Clinopyroxene 18%<br>Opaques 7% | Chlorophaeite 15%<br>Zeolite, clay minerals ) 7% |
| 6 | 77-8 | Basalt (moderately altered) | Very fine grained, amygdaloidal, porphyritic, intersertal | 3%<br>Calcite, chlorite<br>Some pyrite rims, clay, zeolites | 2%<br>Plagioclase (altered to clay) | Plagioclase 35%<br>Opaques 15%<br>Palagonite 25% | Chlorite 8%<br>Calcite 12% |
| 7 | 79-17B | Basalt (moderately altered) | Medium-grained, amygdaloidal, intersertal to subophitic | 15%<br>Zeolites, clay minerals, chlorite | --- | Plagioclase 25%<br>Clinopyroxene 30%<br>Opaques 7% | Chlorophaeite )<br>Chlorite ) 23% |
| 8 | 79-18C | Basalt (highly altered) | Very fine grained, porphyritic, hyalo-ophitic | --- | 2%<br>Plagioclase (altered to clay)<br>Pyroxene (altered to chlorophaeite) | Plagioclase 25%<br>Clinopyroxene 13%<br>Opaques 2%<br>Altered glass 28% | Chlorophaeite )<br>Chlorite ) 30% |

Table 1. Petrography of basalts dredged from the continental slope in the eastern Gulf of Alaska (Continued)

| Map No. (Fig. 1) | Sample Designation | Rock type | Texture | Mineralogy (estimated volume percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Amygdules | Phenocrysts | Groundmass | | | |
| | | | | | | Primary | | Secondary | |
| 8 | 79-18E | Basalt (moderately altered) | Medium-grained, amygdaloidal, subophitic | 35%<br>Chlorite, zeolites, clay minerals | --- | Plagioclase<br>Clinopyroxene<br>Opaques | 20%<br>30%<br>3% | Chlorophaeite | 12% |
| 8 | 79-18F | Basalt (moderately altered) | Fine-grained, amygdaloidal, hyalo-ophitic to intersertal | 10%<br>Zeolites, clay minerals, calcite, chlorite | --- | Plagioclase<br>Clinopyroxene<br>Opaques<br>Palagonite | 25%<br>15%<br>8%<br>25% | Clay minerals<br>Chlorophaeite )<br>Chlorite ) | 12%<br>5% |
| 8 | 79-18D | Basalt (slightly altered) | Medium- to coarse-grained, subophitic | --- | --- | Plagioclase<br>Clinopyroxene<br>Opaques<br>Apatite | 42%<br>32%<br>10%<br>1% | Chlorophaeite )<br>Limonite ) | 15% |

Table 2. Major element chemistry (in weight percent) and normative mineral composition of basalts dredged from the continental slope in the eastern Gulf of Alaska

| Map no. (Fig. 1) | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 6 | 7 | 8 | 8 | 8 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample no. | 7822A3 | 7822A4 | 7822A5 | 7822A7 | 7822A8 | 7940A | 7933G | 7933H | 7934E | 7926F | 7926I | 7926K | 7926L | 77EG8 | 7917B | 7918C | 7918D | 7918E | 7918F |
| $SiO_2$ | 46.50 | 47.70 | 49.50 | 49.10 | 42.40 | 48.30 | 44.80 | 46.40 | 47.80 | 45.40 | 46.50 | 47.10 | 47.60 | 44.80 | 45.70 | 47.10 | 47.30 | 45.10 | 45.70 |
| $Al_2O_3$ | 16.00 | 15.30 | 13.60 | 16.10 | 13.60 | 12.40 | 13.90 | 17.10 | 15.00 | 15.50 | 15.90 | 15.80 | 15.40 | 16.40 | 13.80 | 14.10 | 14.30 | 13.10 | 14.40 |
| $Fe_2O_3$ | 2.51 | 2.30 | 5.20 | 1.88 | 3.10 | 7.96 | 7.30 | 8.09 | 3.91 | 5.54 | 4.45 | 3.76 | 3.80 | 4.30 | 5.37 | 5.25 | 5.50 | 6.16 | 4.50 |
| FeO | 6.54 | 7.90 | 7.70 | 8.21 | 9.70 | 5.34 | 3.80 | 2.35 | 7.01 | 4.73 | 5.35 | 7.41 | 7.60 | 3.80 | 6.86 | 8.32 | 6.10 | 6.15 | 7.20 |
| MgO | 8.48 | 7.60 | 6.50 | 5.58 | 6.40 | 8.06 | 9.00 | 5.80 | 7.51 | 8.10 | 7.61 | 7.78 | 7.00 | 6.60 | 8.04 | 7.19 | 6.50 | 7.18 | 6.90 |
| CaO | 6.32 | 8.30 | 8.90 | 8.28 | 7.60 | 7.09 | 6.70 | 9.18 | 8.81 | 7.40 | 7.48 | 9.96 | 10.10 | 11.20 | 8.55 | 6.34 | 10.20 | 8.67 | 9.00 |
| $Na_2O$ | 3.74 | 2.70 | 4.70 | 3.24 | 4.40 | 4.42 | 5.20 | 3.16 | 3.58 | 4.46 | 3.72 | 2.66 | 4.20 | 3.00 | 3.27 | 3.82 | 3.50 | 3.94 | 4.20 |
| $K_2O$ | 1.41 | 1.60 | 0.16 | 0.15 | 0.07 | 0.36 | 0.52 | 0.31 | 0.72 | 0.59 | 1.39 | 0.57 | 0.53 | 0.37 | 0.67 | 0.36 | 1.40 | 0.46 | 0.41 |
| $\Sigma H_2O$ | 5.04 | 2.94 | 3.30 | 3.69 | 5.87 | 4.47 | 6.19 | 5.23 | 4.44 | 7.63 | 6.80 | 3.60 | 3.24 | 6.00 | 5.82 | 5.22 | 3.90 | 6.50 | 5.90 |
| $TiO_2$ | 1.39 | 1.60 | 1.40 | 1.78 | 2.00 | 1.39 | 1.40 | 1.69 | 1.24 | 0.91 | 0.96 | 1.22 | 1.30 | 1.10 | 1.71 | 2.23 | 1.90 | 1.88 | 1.90 |
| $P_2O_5$ | 0.22 | 0.31 | 0.19 | 0.37 | 0.29 | 0.14 | 0.12 | 0.16 | 0.11 | 0.07 | 0.08 | 0.11 | 0.15 | 0.19 | 0.15 | 0.23 | 0.26 | 0.19 | 0.20 |
| MnO | 0.18 | 0.25 | 0.24 | 0.13 | 0.25 | 0.19 | 0.19 | 0.06 | 0.17 | 0.13 | 0.18 | 0.18 | 0.26 | 0.12 | 0.15 | 0.21 | 0.14 | 0.14 | 0.20 |
| $CO_2$ | 1.88 | 0.04 | 0.02 | 1.35 | 4.20 | 0.12 | 0.03 | 0.24 | 0.11 | 0.22 | 0.18 | 0.09 | 0.01 | 2.10 | 0.10 | 0.32 | 0.02 | 0.18 | 0.02 |
| Total(-O) | 100.21 | 98.54 | 101.41 | 99.86 | 99.88 | 100.24 | 99.15 | 99.77 | 100.41 | 100.68 | 100.60 | 100.24 | 101.19 | 99.98 | 100.19 | 100.74 | 101.02 | 99.65 | 100.53 |
| volatile free -- normalized | | | | | | | | | | | | | | | | | | | |
| $SiO_2$ | 49.84 | 49.92 | 50.46 | 51.78 | 47.21 | 50.50 | 48.21 | 49.20 | 49.86 | 48.91 | 49.67 | 48.78 | 48.60 | 48.76 | 48.48 | 49.47 | 48.71 | 48.51 | 48.30 |
| $Al_2O_3$ | 17.15 | 16.01 | 13.86 | 16.98 | 15.14 | 12.96 | 14.96 | 18.13 | 15.65 | 16.70 | 16.98 | 16.36 | 15.72 | 17.85 | 14.64 | 14.81 | 14.73 | 14.09 | 15.22 |
| $Fe_2O_3$ | 2.69 | 2.41 | 5.30 | 1.98 | 3.45 | 8.32 | 7.86 | 8.58 | 4.08 | 5.97 | 4.75 | 3.89 | 3.88 | 4.68 | 5.70 | 5.51 | 5.66 | 6.63 | 4.76 |
| FeO | 7.01 | 8.27 | 7.85 | 8.66 | 10.80 | 5.58 | 4.09 | 2.49 | 7.31 | 5.10 | 5.71 | 7.67 | 7.76 | 4.14 | 7.28 | 8.74 | 6.28 | 6.62 | 7.61 |
| MgO | 9.09 | 7.95 | 6.63 | 5.88 | 7.13 | 8.43 | 9.68 | 6.15 | 7.83 | 8.73 | 8.13 | 8.06 | 7.15 | 7.18 | 8.53 | 7.55 | 6.69 | 7.72 | 7.29 |
| CaO | 6.77 | 8.69 | 9.07 | 8.73 | 8.46 | 7.41 | 7.21 | 9.73 | 9.19 | 7.97 | 7.99 | 10.32 | 10.31 | 12.19 | 9.07 | 6.66 | 10.50 | 9.33 | 9.51 |
| $Na_2O$ | 4.01 | 2.83 | 4.79 | 3.42 | 4.90 | 4.62 | 5.60 | 3.35 | 3.73 | 4.80 | 3.97 | 2.76 | 4.29 | 3.27 | 3.47 | 4.01 | 3.60 | 4.24 | 4.44 |
| $K_2O$ | 1.51 | 1.67 | 0.16 | 0.16 | 0.08 | 0.38 | 0.56 | 0.33 | 0.75 | 0.64 | 1.48 | 0.59 | 0.54 | 0.40 | 0.71 | 0.38 | 1.44 | 0.49 | 0.43 |
| $TiO_2$ | 1.49 | 1.67 | 1.43 | 1.88 | 2.23 | 1.45 | 1.51 | 1.79 | 1.29 | 0.98 | 1.03 | 1.26 | 1.33 | 1.20 | 1.81 | 2.39 | 1.96 | 2.02 | 2.01 |
| $P_2O_5$ | 0.24 | 0.32 | 0.19 | 0.39 | 0.32 | 0.15 | 0.13 | 0.17 | 0.11 | 0.08 | 0.09 | 0.11 | 0.15 | 0.21 | 0.16 | 0.24 | 0.27 | 0.20 | 0.21 |
| MnO | 0.19 | 0.26 | 0.24 | 0.14 | 0.28 | 0.20 | 0.20 | 0.06 | 0.18 | 0.14 | 0.19 | 0.19 | 0.27 | 0.13 | 0.16 | 0.22 | 0.14 | 0.15 | 0.21 |
| Total(-O) | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| normative minerals -- volatile free | | | | | | | | | | | | | | | | | | | |
| Q | -- | -- | -- | 1.93 | -- | -- | -- | 1.87 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| NE | 1.18 | -- | 0.83 | -- | 5.94 | -- | 7.72 | -- | -- | 4.39 | 1.94 | -- | 5.32 | 0.33 | -- | -- | 2.48 | 1.31 | 3.86 |
| Hy | -- | 9.41 | -- | 21.94 | -- | 8.57 | -- | 10.37 | 1.66 | -- | -- | 10.03 | -- | -- | 4.32 | 17.12 | -- | -- | -- |
| OL | 20.32 | 11.21 | 9.93 | -- | 16.98 | 3.95 | 11.62 | -- | 12.92 | 13.13 | 14.17 | 8.26 | 11.68 | 7.20 | 10.48 | 4.10 | 6.42 | 9.07 | 11.12 |

Table 3. Trace element abundances in parts per million in basalts dredged from the continental slope in the eastern Gulf of Alaska

| Map no. (Fig. 1) | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 6 | 7 | 8 | 8 | 8 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample no. | 7822A3 | 7822A4 | 7822A5 | 7722A7 | 7822A8 | 7940A | 7933G | 7933H | 7934E | 7926F | 7926I | 7926K | 7926L | 77EG8 | 7917B | 7918C | 7918D | 7918E | 7918F |
| * | | | | | | | | | | | | | | | | | | | |
| Ba | 264 | -- | -- | 65 | -- | 23 | -- | 40 | 62 | 20 | 143 | 86 | -- | -- | 80 | 183 | -- | 101 | -- |
| Rb | 14 | -- | -- | 5 | -- | 5 | -- | 5 | 6 | 6 | 15 | 5 | -- | -- | 10 | 5 | -- | 5 | -- |
| Sr | 326 | -- | -- | 232 | -- | 97 | -- | 165 | 276 | 170 | 353 | 194 | -- | -- | 223 | 197 | -- | 146 | -- |
| Nb | 10 | 14 | 6.8 | 15 | 14 | 6 | 7.1 | 7 | 5 | 5 | 5 | 5 | 5.4 | 7.3 | 10 | 11 | 12 | 10 | 10 |
| Zr | 115 | -- | -- | 181 | -- | 82 | -- | 95 | 94 | 62 | 72 | 90 | -- | -- | 104 | 140 | -- | 115 | -- |
| Y | 23 | -- | -- | 32 | -- | 30 | -- | 24 | 25 | 19 | 20 | 25 | -- | -- | 23 | 28 | -- | 28 | -- |
| K/Ba | 44 | -- | -- | 20 | -- | 130 | -- | 64 | 96 | 245 | 81 | 55 | -- | -- | 70 | 16 | -- | 38 | -- |
| K/Rb | 836 | -- | -- | 250 | -- | 598 | -- | 515 | 996 | 816 | 769 | 946 | -- | -- | 556 | 598 | -- | 764 | -- |
| Rb/Sr | 0.04 | -- | -- | 0.02 | -- | 0.05 | -- | 0.03 | 0.02 | 0.04 | 0.04 | 0.03 | -- | -- | 0.05 | 0.03 | -- | 0.03 | -- |
| Zr/Nb | 11.5 | -- | -- | 12.1 | -- | 13.7 | -- | 13.6 | 18.8 | 12.4 | 14.4 | 18.0 | -- | -- | 10.4 | 12.7 | -- | 11.5 | -- |
| ** | | | | | | | | | | | | | | | | | | | |
| Cr | 160 | 231[1] | 233[1] | 59 | 34[1] | 81 | 244[1] | 120 | 160 | 210 | 170 | 180 | 214[1] | 181[1] | 200 | 92 | 203[1] | 140 | 143[1] |
| Ni | 100 | 72[2] | 67[2] | 60 | 22[2] | 56 | 55 | 79 | 58 | 71 | 56 | 58 | 43[2] | 140[2] | 130 | 67 | 76[2] | 84 | 67[2] |
| Sc | 33 | 40[1] | 44[1] | 29 | 39[1] | 47 | 45[1] | 47 | 41 | 41 | 39 | 46 | 45 | 34[1] | 41 | 40 | 43[1] | 38 | 40[1] |
| *** | | | | | | | | | | | | | | | | | | | |
| La | 8 | 10 | 4 | 15 | 10 | 5 | 4 | 6 | 5 | 3 | 4 | 5 | 6 | 6 | 8 | 12 | 10 | 9 | 9 |
| Ce | 19 | 24 | 11 | 35 | 24 | 11 | 11 | 14 | 12 | 7 | 9 | 11 | 14 | 13 | 1.8 | 25 | 25 | 20 | 23 |
| Sm | 3.6 | 3.9 | 2.7 | 4.6 | 4.3 | 3.1 | 2.6 | 3.5 | 3.2 | 2.0 | 2.4 | 3.0 | 2.8 | 2.4 | 4.0 | 5.1 | 4.0 | 4.3 | 3.6 |
| Eu | 1.1 | 1.4 | 1.1 | 1.7 | 1.5 | 1.1 | 1.1 | 1.2 | 1.0 | 0.7 | 0.8 | 1.0 | 1.2 | 1.0 | 1.3 | 1.6 | 1.6 | 1.4 | 1.4 |
| Tb | 0.7 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.7 | 0.5 | 0.6 | 0.7 | 0.8 | 0.6 | 0.8 | 0.9 | 0.9 | 0.8 | -- |
| Yb | 2.5 | 3.4 | 3.8 | 2.8 | 4.3 | 3.4 | 2.7 | 2.9 | 3.0 | 2.0 | 2.4 | 2.8 | 3.3 | 2.2 | 2.6 | 3.2 | 3.3 | 2.9 | 3.1 |
| Lu | 0.37 | 0.52 | 0.56 | 0.40 | 0.64 | 0.51 | 0.42 | 0.41 | 0.46 | 0.28 | 0.35 | 0.41 | 0.53 | 0.36 | 0.40 | 0.49 | 0.47 | 0.41 | 0.44 |
| Ta | 0.7 | 0.9 | 0.3 | 1.2 | 0.8 | 0.3 | 0.4 | 0.4 | 0.3 | 0.2 | 0.2 | 0.3 | 0.4 | 0.4 | 0.6 | 0.9 | 0.9 | 0.7 | 0.8 |
| Th | 0.4 | 0.4 | 0.3 | 0.5 | 0.6 | 0.3 | 0.4 | 0.4 | 0.5 | 0.3 | 0.3 | 0.5 | 0.6 | 0.4 | 0.7 | 0.9 | 1.0 | 0.7 | 0.8 |
| Hf | 2.7 | 3.3 | 2.1 | 4.4 | 3.4 | 2.0 | 2.1 | 2.5 | 2.3 | 1.5 | 1.8 | 2.2 | 2.5 | 1.8 | 2.6 | 3.5 | 3.4 | 3.0 | 3.1 |
| La/Yb | 3.2 | 2.9 | 1.1 | 5.4 | 2.2 | 1.5 | 1.5 | 2.1 | 1.7 | 1.5 | 1.7 | 1.8 | 1.8 | 2.7 | 3.1 | 3.8 | 3.0 | 3.1 | 2.9 |
| $La_N/Sm_N$ | 1.2 | 1.4 | 0.8 | 1.8 | 1.3 | 0.8 | 0.9 | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 1.1 | 1.3 | 1.0 | 1.2 | 1.4 | 1.2 | 1.4 |

* Determined by XRF.

** Determined by emission spectroscopy, except where indicated (1) by INAA and (2) by XRF.

*** Determined by instrumental neutron activation analysis.

Table 4. Representative clinopyroxene analyses of basalts dredged from the continental slope in the eastern Gulf of Alaska

| Sample no. | 7822A4 | 7822A7 | 7940A | 7933H | 7934E | 7926L | 7917B | 7918D |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 50.7 | 50.6 | 50.6 | 51.2 | 50.8 | 51.2 | 51.7 | 51.2 |
| $Al_2O_3$ | 2.78 | 2.68 | 3.23 | 3.35 | 3.41 | 3.67 | 3.45 | 1.94 |
| $TiO_2$ | 0.89 | 0.88 | 0.90 | 0.80 | 0.44 | 0.66 | 0.86 | 0.94 |
| "FeO" | 9.09 | 9.04 | 8.05 | 7.57 | 6.24 | 8.66 | 9.5 | 12.7 |
| MnO | 0.31 | 0.28 | 0.21 | 0.20 | 0.28 | 0.25 | 0.20 | 0.36 |
| MgO | 15.8 | 16.2 | 17.3 | 16.6 | 16.6 | 15.7 | 15.4 | 14.4 |
| CaO | 19.3 | 18.9 | 18.9 | 18.8 | 20.5 | 18.9 | 19.7 | 18.7 |
| $Na_2O$ | 0.34 | 0.33 | 0.25 | 0.29 | 0.33 | 0.33 | 0.32 | 0.32 |
| $Cr_2O_3$ | 0.08 | 0.18 | 0.03 | 0.28 | 0.60 | 0.38 | 0.28 | 0.05 |
| SUM | 99.3 | 99.1 | 99.5 | 99.1 | 99.1 | 99.8 | 101.4 | 100.6 |
| FeO | 6.54 | 6.53 | 4.95 | 6.71 | 3.28 | 7.76 | 8.21 | 10.91 |
| $Fe_2O_3$ | 2.84 | 2.79 | 3.45 | 0.84 | 3.29 | 0.99 | 1.47 | 1.93 |
| Si | 1.886 | 1.889 | 1.886 | 1.902 | 1.870 | 1.894 | 1.889 | 1.910 |
| $Al^{IV}$ | 0.114 | 0.109 | 0.134 | 0.098 | 0.130 | 0.106 | 0.111 | 0.085 |
| $Al^{IV}$ | 0.007 | 0.000 | 0.006 | 0.048 | 0.019 | 0.054 | 0.038 | 0.000 |
| Ti | 0.025 | 0.025 | 0.025 | 0.020 | 0.012 | 0.018 | 0.024 | 0.026 |
| Cr | 0.002 | 0.005 | 0.001 | 0.008 | 0.018 | 0.011 | 0.008 | 0.001 |
| $Fe^{3+}$ | 0.079 | 0.078 | 0.096 | 0.024 | 0.092 | 0.028 | 0.041 | 0.054 |
| $Fe^{2+}$ | 0.203 | 0.204 | 0.152 | 0.208 | 0.102 | 0.240 | 0.251 | 0.341 |
| Mn | 0.010 | 0.009 | 0.007 | 0.006 | 0.007 | 0.008 | 0.006 | 0.011 |
| Mg | 0.879 | 0.903 | 0.950 | 0.917 | 0.916 | 0.868 | 0.836 | 0.802 |
| Ca | 0.769 | 0.756 | 0.746 | 0.748 | 0.812 | 0.749 | 0.775 | 0.750 |
| Na | 0.025 | 0.024 | 0.018 | 0.021 | 0.024 | 0.024 | 0.023 | 0.023 |
| Ca | 39.9 | 38.9 | 38.6 | 39.5 | 42.3 | 39.8 | 40.8 | 38.5 |
| Mg % | 45.6 | 46.5 | 46.1 | 48.3 | 47.7 | 46.1 | 43.9 | 41.2 |
| ΣFe | 14.5 | 14.5 | 15.4 | 12.2 | 10.1 | 14.2 | 15.3 | 20.3 |