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A RECONNAISSANCE STUDY OF THE U AND TH CONTENTS OF PLUTONIC ROCKS OF THE SOUTHEASTERN SEWARD PENINSULA, ALASKA

By

Thomas P. Miller, 1938- and Carl Maurice M. Bunker, 1922-

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Abstract

Large granitic Cretaceous plutons are exposed along and adjacent to an arcuate belt of igneous and high-grade metamorphic rocks in the southeastern Seward Peninsula of Alaska. Reconnaissance studies of these plutons have shown that the Darby pluton has well above average amounts of U and Th (11.2 ppm and 58.7 ppm respectively), the Kachauik pluton ranges from average to above average U and Th (5.7 ppm and 22.5 ppm respectively), and the Bendeleben pluton contains average amounts of U and Th (3.4 ppm and 16.7 ppm respectively). The three plutons show compositional and textural differences indicative of different source materials which may have controlled the distribution of U and Th.

The high U and Th contents of the Darby pluton, similar to that of the Conway Granite of New Hampshire which has been mentioned as a possible low grade Th resource, suggests that this pluton may be a favorable area for economic concentrations of U and Th.

Introduction

Reconnaissance sampling and mapping of three large granitic masses, the Bendeleben, Darby, and Kachauik plutons, in the southeastern part of the Seward Peninsula (fig. 1) has shown that the Darby pluton has above average U and Th contents and that U and Th contents of the three plutons are significantly different. Reconnaissance petrologic studies of the three plutons and analytical results reported herein provide a framework for future studies of radioactive materials in the region and call attention to areas of anomalous concentrations of U and Th.

The southeastern Seward Peninsula is dominated physiographically by the rugged Bendeleben and Darby Mountains which together form an arcuate trend convex to the southwest. The Darby and Bendeleben plutons underlie the respectively named mountain ranges while the Kachauik pluton lies in the uplands adjacent to the Darby Mountains. These plutons were first noted by Mendenhall (1901) and Smith and Eakin (1911) during reconnaissance traverses along and across the Darby Mountains. No other studies of these plutons were done until West (1953) investigated the radioactivity of pan concentrates taken from streams draining the Darby and Kachauik plutons. More recently, the plutons were mapped at a scale of 1:250,000 by Miller and others (1972) and much of this report is based on that work. A preliminary geochemical report by Miller and Grybeck (1973) mentioned the high U and Th values obtained from 3 rock samples of the Darby pluton.

Approximately 70 modal analyses have been made of the plutonic rocks and 28 chemical analyses were obtained along with the 31 gamma-ray spectrometric analyses reported here. It is emphasized that much of this study is based upon reconnaissance mapping and the number of samples analyzed is too small to define in detail the total range of U and Th contents in the plutons sampled. Smaller plutons in the general region such as the Windy Creek stock and the Dry Canyon Creek alkaline complex (fig. 1) have not been sampled for U and Th.

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Geologic Setting

The Darby, Bendeleben, and Kachauik plutons are among the largest bodies of granitic rock on the Seward Peninsula and form part of an arcuate belt of plutonic and high-grade metamorphic rocks extending for 270 km across the Peninsula through the Darby, Bendeleben, and Kigluaik Mountains (fig. 1). The metamorphic rocks of this igneous-metamorphic complex consist chiefly of Precambrian pelitic schist and gneiss with intercalated marble, calc-silicate gneiss, and minor amphibolite; mineral assemblages suggest the rocks belong to the almandine amphibolite facies. The plutonic rocks that intrude this assemblage in the southeastern Seward Peninsula are chiefly Cretaceous and range in composition from quartz monzonite and granodiorite to monzonite and syenite. Associated with some of the syenite and monzonite bodies are small intrusive complexes and dikes of alkaline subsilicic rocks which form part of a lithologically similar belt that extends from west-central Alaska through the southeastern Seward Peninsula and St. Lawrence Island into Siberia (Miller, 1972; Csejtey and Patton, 1974). Bounding the igneous-metamorphic complex in the southeastern Seward Peninsula are low-grade Precambrian greenschist facies rocks, consisting chiefly of quartz-mica schist with lesser amounts of metavolcanic rocks, graphitic schist, and marble. Paleozoic (chiefly Devonian) carbonate rocks (Miller and others, 1972) are associated with these low-grade metamorphic rocks and appear to be in fault contact with them. The change in facies between low- and high-grade metamorphic rocks is so abrupt in most places that it appears to mark a fault contact. Cretaceous non-marine sedimentary rocks crop out east of the Darby Mountains and Late Cenozoic basalts, which cover large areas to the north and east, occur locally in the southeastern Seward Peninsula. Both the Bendeleben and Darby Mountains were subjected to valley glaciation of probable Illinoian and Wisconsin age (Hopkins, 1963) which has resulted in numerous U-shaped valleys and aretes.

The southeastern Seward Peninsula is structurally complex and its dominant structural grain changes from east-west in the Bendeleben Mountains to north-south in the Darby Mountains. Parts of the area have been subjected to east-directed thrust-faulting (Sainsbury, 1969b) and both mountain ranges appear to be at least partly bounded by range-front faults. A narrow but continuous north-south belt of ophiolite rocks of probable Permian age crops out east of the Darby and Bendeleben Mountains (Miller and others, 1972); these rocks are locally glaucophane-bearing and may mark an old suture zone.

Petrology

The Darby and Bendeleben plutons are composed of relatively homogeneous quartz monzonite that is similar in gross composition but differs in grain size and texture. The Kachauik pluton is a much more heterogeneous composite pluton composed of rocks ranging from granodiorite to syenite. Plots of felsic modal components based on point counts of stained slabs (fig. 2) show the compositional character of the plutons. Because the sampling density of these large plutons is relatively low, the modes shown in figure 2 only approximately represent the range in composition. The same is true for the average chemical analyses given in Table 1.

The Darby pluton underlies the eastern Darby Mountains and has a rather unusual shape - a long thin body extending for over 80 km in a N 18° E direction and only 3 to 8 km wide covering an area of about 400 km^2. Exposures are good in the glaciated northern part of the pluton, particularly in the higher cirque walls, and along the southern sea coast; elsewhere in the pluton, frost action has reduced many outcrops to frost-riven blocks. Enough tor-like pinnacle outcrops remain, however, to give a fair outcrop pattern. The rocks are generally fresh although commonly somewhat friable in the pinnacle outcrops. The Darby granitic rocks have a distinct and characteristic coarse-grained and porphyritic texture with large tabular pink K-feldspar phenocrysts (up to 50 mm long) in a gray to cream colored, medium- to coarse-grained groundmass of feldspar and quartz mottled with 5 to 10 percent dark minerals. Foliation and lineation are almost totally lacking except locally along the western contact north of the headwaters of Dry Canyon Creek. Large (>30 cm in length) mafic ellipsoidal inclusions are locally very abundant in the sea cliff exposures at the southern tip of the pluton just east of Cape Darby (fig. 1).

The Darby granitic rocks are chiefly quartz monzonite consisting essentially of perthitic K-feldspar and plagioclase (An_{20-34}) in approximately equal amounts with slightly less quartz. Varietal mafic minerals are biotite and hornblende with hornblende always less abundant than biotite and almost totally absent in the northern third of the pluton. Ubiquitous accessory minerals are abundant magnetite and allanite with lesser amounts of sphene, apatite, zircon, and a little fluorite and rutile. Alteration effects are weak with only minor amounts of sericite after plagioclase, chlorite after biotite, and goethite and lepidocrocite after magnetite.

Although megascopically the pluton appears to show little change in composition over its entire 80 km length, the modes show a slight and gradual decrease in mafic mineral and plagioclase content from south to north and a corresponding increase in quartz and K-feldspar indicating lateral zoning. This lateral zoning is illustrated in Figure 3 where mafic mineral content is plotted along the axis of the pluton.

Aplite dikes, commonly tourmaline-bearing and generally less than 40 cm thick, are common throughout the pluton, and a swarm of lamprophyre dikes occurs near the south end of the pluton.

The most distinguishing characteristics of the Darby pluton are its uniform coarse-grained and porphyritic texture, consistent mineralogy, relatively homogeneous composition, and relative abundance of magnetite and allanite. Chemically the Darby granitic rocks are SiO_2- and K_2O-rich with a high Fe_2O_3/FeO ratio. This high Fe_2O_3/FeO ratio is reflected in the abundant magnetite in the Darby pluton which in turn results in a high magnetic intensity for the pluton particularly as compared to the Bendeleben pluton (Alaska Div. Geol. and Geophys. Surveys, 1973a, b).

The Bendeleben pluton forms the core of the eastern Bendeleben Mountains underlying an ellipsoidal-shaped area of about 300 km^2. Exposures of rock actually in place are generally confined to the higher cirque walls as frost-action has resulted in the destruction of most outcrops to frost-riven blocks. Most of the Bendeleben granitic rocks are fine- to medium-grained, pinkish-gray quartz monzonite mottled with up to 11 percent mafic minerals. The rock is generally massive and equigranular although porphyritic and foliated varieties occur near the border of the pluton.

In contrast to the abrupt country-rock contacts of the Darby pluton, the Bendeleben body consists of a central core of granitic rocks enclosed in a broad zone of alternating thin bands of granitic and high-grade metamorphic rocks with the latter gradually increasing away from the pluton. Aplite dikes cut both the pluton and country rocks and pegmatites are also common in the country rock.

The Bendeleben quartz monzonite consists essentially of plagioclase (An_{25-37}) and slightly lesser amounts of perthitic K-feldspar and quartz. The varietal mafic minerals, biotite and hornblende, make up about 7 percent of the rock. Both biotite and hornblende are present, but biotite is generally much more abundant as shown by a biotite/hornblende ratio of over 9. Locally, in more mafic and perhaps contaminated phases, hornblende is more abundant and clinopyroxene also occurs. Accessory minerals are sphene, zircon, and apatite. Allanite and opaque minerals are less common and much less abundant than in the Darby pluton; monazite is a rare constituent.

Distinguishing characteristics of the Bendeleben pluton are its relatively fine-grained and equigranular texture and its relative paucity of magnetite and allanite as compared to the Darby pluton. Chemically the Bendeleben quartz monzonite is a silicic quartz monzonite with a low Fe_2O_3/FeO ratio.

The Kachauik pluton occupies the upland region west of the Darby Mountains and has an aggregate area of about 530 km^2 (fig. 1). It is a composite intrusion with granodiorite and quartz monzonite forming most of the west half of the pluton and a monzonite-syenite unit, subdivided by Miller and others (1972) into four sub-units, forming the eastern part. An alkaline rock dike swarm consisting of pulaskite and pseudoleucite porphyry has intruded much of the northern half of the pluton (Miller and others, 1971); the dike set has a consistent N 40° E strike. Exposures of rock actually in place are confined chiefly to scattered tor-like outcrops that are commonest in the coarse-grained monzonite-syenite unit.

The granodiorite and quartz monzonite are porphyritic with large cream colored plagioclase phenocrysts up to 25 cm long and abundant mafic mineral phenocrysts in a grayish-cream colored medium-grained groundmass of feldspar and quartz. Essential minerals are plagioclase (An_{33-45}), perthitic orthoclase, and less abundant quartz; varietal mafic minerals which constitute up to 27 percent of the rock, are biotite, hornblende, and clinopyroxene. The average modal composition is approximately that of a granodiorite. Adjacent to the alkaline rock dikes, the granodiorite has commonly been metasomatized with incipient development of aegirine and riebeckite. Accessory minerals are ubiquitous sphene, zircon, and apatite; allanite is less common, and magnetite is rare. Tourmaline is common in the form of thin veinlets cutting feldspar.

Distinguishing characteristics of the granodiorite are the large cream-colored plagioclase phenocrysts, relatively low quartz content, the occurrence of clinopyroxene with hornblende and biotite, the almost total lack of magnetite, the tourmaline veinlets, and the local alkali metasomatized rocks.

The two chemical analyses reported in Table 1 are of granodiorite in which little or no alkali metasomatism is apparent. They show the unaltered rock to be a fairly mafic-rich granodiorite relatively low in SiO_2 and high in K_2O. Metasomatized rocks show lower SiO_2 but higher alkalies.

The monzonite-syenite unit is very heterogeneous and composed of a variety of rocks including obvious contaminated and hybrid phases. Rocks of this unit are characteristically porphyritic with large pink to cream-colored K-feldspar phenocrysts (up to 75 mm long) in a similar colored medium-grained groundmass of feldspar; large hornblende and pyroxene phenocrysts are also abundant. Trachytoid and gneissic textures caused by alignment of K-feldspar phenocrysts and grains are common.

Essential minerals are perthitic K-feldspar and subordinate plagioclase (An_{30-45}); quartz ranges from absent up to 5 percent. Varietal mafic minerals are dark green-brown hornblende and green clinopyroxene; biotite is rare except in hybrid phases and melanite garnet is locally present in contaminated border phases. Accessory minerals are ubiquitous sphene, apatite, and zircon, sporadically distributed magnetite, and allanite.

Distinguishing characteristics of the monzonite-syenite unit are the high K-feldspar and mafic mineral content and the variation in composition and texture. The chemical analyses in Table 1 show the general low SiO_2, high K_2O character of the rock as well as its generally more mafic character as indicated by relatively high FeO, Fe_2O_3, MgO and CaO contents.

Age of plutons

The plutons of the southeast Seward Peninsula intrude rocks of probable Precambrian age and are not stratigraphically bracketed. Although K-Ar dates have been obtained from the plutons in the area, only on the Darby pluton has sufficient dating been done to be relatively confident of the age. Two biotite samples from the northern part of this pluton yield ages of 92.1± 2.8 and 94.0± 3 m.y. (table 2) and coexisting hornblende and biotite from a sample from the middle of the pluton yield ages of 92.8± 2.6 and 88.3± 1.5 m.y. respectively. These latter two ages, although not quite within the range of analytical error, together with the two biotite dates indicate, a Late Cretaceous age of 88 to 94 m.y. for the pluton. A previously reported hornblende date of 81.4± 3 m.y. for the Darby pluton (Miller and others, 1972) appears to be in error due to an incorrect K_2O analysis.

A date of 79.8± 2.4 m.y. has been obtained on biotite from the Bendeleben pluton and a date of 97.5± 3 m.y. has been obtained on hornblende from the monzonite-syenite unit of the Kachauik pluton (table 2). These dates should only be regarded as preliminary until supporting K-Ar age data are obtained; however, they are similar to those reported on plutons of similar composition elsewhere in western Alaska (Miller, 1970a; Csejtey and others, 1971). Also, that part of the Kachauik pluton adjacent to the Darby pluton is intruded by dikes similar in composition to the Darby granitic rocks indicating that the Kachauik rocks are older.

The absolute age of the granodiorite unit of the Kachauik pluton is uncertain. Although an age of 86.1± 3 m.y. has been reported on hornblende from this unit (Miller and others, 1972), a biotite sample from a nepheline syenite dike intruding this unit has since yielded a 93.9± 3 m.y. age. Additional age dating is currently being conducted on this unit in an attempt to resolve this problem. K-Ar dates from other alkaline rocks in the western Alaska alkaline rock province, including the nearby Dry Canyon Creek stock (fig. 1), have yielded ages of 105 to 107 m.y. (Miller, 1972).

The K-Ar ages on these three large plutons range from 80 m.y. to 98 m.y. suggesting emplacement in Cretaceous time. The Kachauik pluton is similar in composition to a suite of plutons in western Alaska that has yielded K-Ar ages of 98 to 110 m.y. (Miller, 1972) and the single available date of 98 m.y. from the Kachauik pluton indicates it belongs to this suite. A Late Cretaceous time of emplacement of around 92 m.y. for the Darby pluton appears to be fairly well documented by the four K-Ar ages obtained from the pluton. Csejtey and others (1971) refer to a 93 m.y. age for a mineralized granitic pluton on St. Lawrence Island and the Kugruk pluton (Sainsbury, 1974) north of the Bendeleben Mountains has likewise yielded a 93 m.y. age (T. P. Miller, unpublished data). The relationship of the Bendeleben pluton to other nearby plutonic rocks is uncertain since only a single date of 80 m.y. is available. A suite of calc-alkaline granitic rocks has yielded ages of 78 to 82 m.y. in the Yukon-Koyukuk province to the east, (Miller, 1970b) and a date of 75 m.y. has been reported on the Brooks Mountain granitic stock in the western Seward Peninsula (Sainsbury, 1969a).

Distribution of U and Th

Analytical Method

Uranium, thorium, and potassium analyses of 31 samples from the Darby, Bendeleben, and Kachauik plutons are tabulated in Table 3. These analyses were done by gamma-ray spectrometry and the basic operational procedures and calibration techniques are described by Bunker and Bush (1966).

Uranium concentrations are determined indirectly by measuring the radium daughters to obtain radium equivalent uranium (RaeU) values. Radium equivalent uranium is the amount of uranium, under the assumption of radioactive equilibrium, required to support the amount of daughter products that emit the radioactivity measured in a sample. Throughout the report where "U" and "uranium" are used "radium equivalent uranium" is implicit. Although thorium is also measured from daughter products, disequilibrium is improbable because of short half-lives; therefore, the concentrations are considered to be a direct measurement of parent thorium. Potassium is determined from its K^{40} content, which is proportional to the total potassium. The coefficients of variation for the accuracy of the data included in this report (table 3) are about 3 percent for uranium and thorium and 1 percent for potassium when compared to standards analyzed by isotope dilution and flame photometer methods.

The Darby pluton has the highest U and Th content of the three plutons with an average of 11.2 and 58.7 ppm respectively or about 2 to 3 times various reported averages (Rodgers and Adams, 1969) for granitic rocks. The U and Th content appears to be high over the entire 80 km length of the pluton; samples D1 and D13 (fig. 1), for example, are about 75 km apart, yet show 7.92 ppm U and 55.15 ppm Th and 14.61 ppm U and 52.92 ppm Th respectively. The consistency of high values is also indicated by the range in U and Th which is 6.18 to 19.89 ppm for U and 40.84 to 83.75 ppm Th. The number of samples is too small to definitely pinpoint any local areas within the pluton with significantly higher U and Th; however, samples D3, D4, and D5 just west of Vulcan Creek in the northern part of the pluton

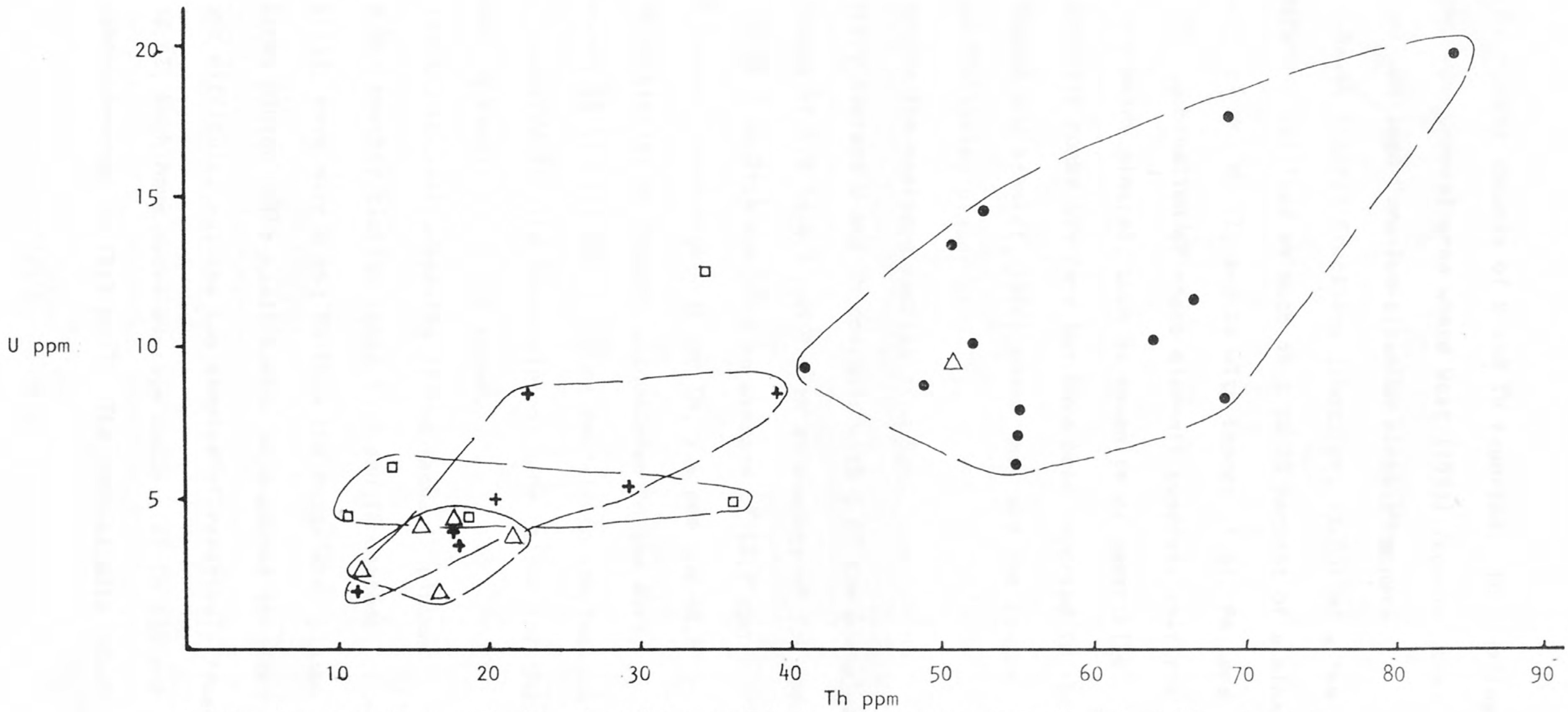

Figure 5. U content of Darby, Bendeleben and Kachauik plutons plotted against Th. Symbols are the same as Figure 4.

include some of the highest amounts of U and Th reported. Interestingly enough, this is the same general area where West (1953) reported the occurrence of an unidentified "uranium-titanium niobate" mineral in pan concentrates. Heavy mineral fractions (spec. gr. >2.89) of a few of the pan concentrates contained as much as 5 to 10 percent of a mineral that consists chiefly of Nb, U, Ti, and Ca with traces of Si, Fe, and Th (West, 1953). The combination of these elements suggests that the mineral is a multiple oxide mineral, such as euxenite or samarskite. Euxenite-bearing granitic rocks are rare but have been reported in the Idaho batholith (Mackin and Schmidt, 1956) where they are the source material for U- and Th-bearing placer deposits.

With one exception the analyzed samples from Bendeleben pluton contain approximately average U and Th contents with 5 of the 6 analyzed samples showing a range of 1.8 to 4.4 ppm U with an average of 3.4 ppm and a range in Th of 11.7 to 21.4 ppm with an average of 16.7 ppm. Sample B4 (fig. 1) contains much higher U and Th, 9.5 ppm and 50.8 ppm respectively, which is similar to amounts encountered in the Darby pluton; the K content, however, is similar to the other Bendeleben samples and less than any value of K reported for the Darby pluton. The reason for the high U and Th content in sample B4 is not known.

The granodiorite and monzonite-syenite of the Kachauik pluton show a considerable but roughly similar range in U and Th content. The Kachauik rocks generally have more U and Th than the Bendeleben pluton but less than the Darby pluton. The small number of analyzed samples makes generalizations difficult, but the two samples of relatively fresh granodiorite, K1 and K2, both have above average amounts of Th (36 and 34 ppm) and K2 has above average U (12.5 ppm). The samples with lower quartz content and visible signs of K- and Na-metasomatism contain lesser amounts of U and Th.

Variation diagrams indicating the relationship between U, Th, and K are given in Figs. 4 and 5 and show that for the Bendeleben pluton and for the granodiorite of the Kachauik pluton, Th generally increases as K increases. Such an increase is common for igneous rock series as Th and U generally increase as differentiation proceeds and the K content in silicic rocks such as these serves as a differentiation index. For the K-rich monzonite-syenite of the Kachauik pluton, however, the trend is anomalous in that Th decreases as K increases. The range of K for the Darby pluton is so small that no trend relative to Th is discernable.

Individual units show little or no relationship between U and K but, excluding the monzonite-syenite of the Kachauik pluton, the plutons as a whole show a general increase of U with respect to K. The Kachauik monzonite-syenite shows little variation of U with respect to K.

The Darby pluton has the highest U/K and Th/K ratios (table 3) which is to be expected since it is composed of the most silicic, and presumably the most highly differentiated rock of the three plutons, and U/K and Th/K characteristically increase as rocks become more differentiated K (Rodgers and Adams, 1969). A fairly good positive correlation exists between U and Th in the Darby pluton (fig. 5); The U/Th ratio is the highest of the three plutons and relatively high for granitic rocks in general. A similar relationship appears to exist for the Kachauik monzonite-syenite whereas no clear trend is apparent for the Kachauik granodiorite or the Bendeleben quartz monzonite.

Radiogenic heat produced by the plutonic rocks from the southeast Seward Peninsula has been calculated (table 3) from the U, Th, and K contents (table 3) on the basis of Birch's estimates (1954) of heat generation (1 ppm Th = 0.20 µcal/g yr [micro calories per gram per year]; 1 ppm U = 0.73 µcal/g yr; 1 percent K = 0.27 µcal/g yr). The Darby pluton, as is to be expected from its high U, Th, and K content has the greatest heat production. The heat yield from this pluton ranged from 16.0 to 32.4 µcal/g yr and averages 21. This range is considerably above typical values reported for granitic rocks from the western U. S. by Tilling and Gottfried (1969). For example, the Boulder batholith has a reported average heat production of 6.8 µcal/g yr, and the southern California batholith of 2.7 µcal/g yr. The Kachauik pluton has a lower average heat production of about 10 µcal/g yr and the Bendeleben pluton has an average heat production of 8.67 µcal/g yr (6.7 µcal/g yr excluding sample B4), which is more typical of granitic rocks.

All three plutons contain common accessory minerals such as allanite, sphene, and zircon that are typically host minerals for U and Th. West (1953) reported that the radioactivity of the concentrates taken from streams draining the Kachauik and Darby plutons was largely due to these accessory minerals. The Darby pluton has a much higher U and Th content than the Bendeleben and Kachauik plutons, and allanite is certainly more abundant in the Darby pluton than in either of the other two plutons. A quantitative spectrographic analysis of allanite from sample D10 showed 12,000 ppm Th.

Assuming an average Th content for the remaining accessory minerals as well as the major minerals present, a total of 0.4 to 0.5 percent allanite would have to be present in order to account for the 67 ppm

Th reported for sample D10. Point counts of the amount of allanite in the rock range from 0.15 to 0.21 percent. This estimate of the amount of allanite may be too low since accurate estimates of modal abundance of accessory minerals based on thin section study are difficult to obtain. This would be particularly true in regard to the coarse-grained Darby rocks. Other possibilities are that one of the major minerals in the rock contains much more Th than is typically the case, or an as yet unidentified U- and Th-bearing mineral is present. X-ray studies of heavy mineral concentrates from this sample do not reveal any such minerals, however, nor has West (1953) reported any, other than the euxenite-like mineral, in the pan concentrates.

Discussion

The present study has shown that the Darby pluton has well above average U and Th, the Kachauik pluton varies from average to slightly above average, and the Bendeleben pluton has only average U and Th content. The reason for the variation in U and Th among plutons as close together as these is not readily apparent but may be a reflection of a difference in U and Th content of the pre-granitic source rocks of the three plutons.

It has been suggested, for example, that the decrease in the U content and radioactivity from east to west across the Sierra Nevada batholith, noted by Dodge (1972) and Wollenberg and Smith (1968) among others, reflects a regional distribution of U and Th that predates the intrusion of the granitic rocks (Wollenberg and Smith, 1968). In the southeastern Seward Peninsula, however, the same sillimanite-bearing high-grade metamorphic rock unit occurs in the country rock surrounding all three plutons. The plutons, underlying an aggregate area of over

1200 sq km, occur within a relatively small area of 7000 km^2 and vary in composition from highly silicic quartz monzonite to subsilicic nepheline syenite and in age from 105 m.y. to 80 m.y. This close juxtaposition of plutonic rocks that differ considerably in major or minor element composition but cover a time interval of only 25 m.y. and intrude the same country rock makes it unlikely that their composition results from lateral variation in the pre-granitic source rocks. A more likely possibility is a vertical variation in the composition of the pre-granitic source rocks coupled with the formation of magma at different levels. The high potassium, low silica, and general more mafic character of the Kachauik pluton, for example, suggests that the source material for the Kachauik pluton, be it crustal material, deep-seated magma, or a combination of the two, was considerably different from the other two plutons. The close association in time and space of the large monzonite-syenite plutons (Kachauik-type rocks) in western Alaska with a regional belt of alkaline subsilicic rocks has lead to the suggestion (Miller, 1972) that the composition of the former is due at least partly to deep-seated alkaline magmas.

The Darby and Bendeleben plutons also show some indications that their respective magmas formed at different levels. The two plutons are relatively similar in gross composition with the Darby pluton being slightly higher in K_2O and Na_2O and the Bendeleben slightly higher in CaO and Al_2O_3. Perhaps the most significant chemical difference between the two plutons, however, is in their respective Fe_2O_3/FeO ratios. Although their total Fe content is about the same, the Darby pluton has an average Fe_2O_3/FeO ratio of 1.08 compared with 0.16 in the Bendeleben pluton. Converting the Fe_2O_3/FeO ratio to the molecular ratio $(2Fe_2O_3 \times 100)/(2Fe_2O_3 + FeO)$, termed the oxidation ratio by Chinner (1960), gives some insight into the behavior of oxygen during magmatic processes. The oxidation ratio appears to be dependent on the magnetite content and the Darby pluton contains much more magnetite than the Bendeleben pluton; this dependence is similar to that pointed out by Dodge (1972) for the Sierra Nevada batholith. The average oxidation ratio for the Darby pluton is 50 as compared to 13 for the Bendeleben pluton which indicates that the Darby pluton had a higher oxygen pressure and thus a higher degree of water saturation, although neither magma was probably water saturated. This difference in water saturation of the magmas may be a reflection of the water content of the pre-granitic source rocks. If more anhydrous rocks are to be expected at depth, for example, then the Bendeleben magma was formed at depths greater than that of the Darby magma.

Alkaline rocks are commonly host rocks for U and Th deposits, and the western Alaska alkaline province with its associated large monzonite and syenite plutons were included within a U-Th metal province which extends 300 km north and east of the southeastern Seward Peninsula (Clark and others, 1972). Uranothorianite and gummite were found associated with copper sulfides, molybdenite, gold, silver, bismuth and thorite in placer deposits in the headwaters of the Peace River within this province (Gault and others, 1953). The streams in this area drain a mineralized alkaline stock (Miller and Elliott, 1969). U and Th analysis of selected plutonic rocks from plutons and alkaline complexes located within this U-Th province are as great as 31 ppm U and 179 ppm Th (Miller and Bunker, 1975).

The occurrence of above average amounts of U and Th in the Darby pluton shows that anomalous amounts of U and Th in this part of Alaska are not necessarily confined to alkaline and kindred intrusive rocks. The Darby pluton is slightly younger than the alkaline rocks and is much more silicic. This close spatial association of two different rock types both with above average U and Th indicates that the area is indeed a U-Th province and that this part of the crust is enriched in U and Th.

Other occurrences of U and Th have been reported elsewhere in the Seward Peninsula. Small stocks of pyroxene-bearing granitic rocks in the Kigluaik and western Bendeleben Mountains have been described by Sainsbury (1974) as being unusually rich in Th and containing abundant allanite. West and White (1952) reported the occurrence of zeunerite, a secondary hydrous copper-uranium arsenate mineral, in a small granitic stock at Brooks Mountain in the western Seward Peninsula. Most of the zeunerite is disseminated in hematite which partly fills openings in an oxidized pegmatitic phase of the intrusion. The primary source of the uranium is not known. Moxham and West (1953) reported small amounts of radioactive material in Serpentine Hot Springs pluton of the northwest Seward Peninsula which result in above average radioactivity. Sainsbury and others (1970) state that the southeastern edge of the Serpentine Hot Springs pluton has the highest radioactivity. Killeen and Ordway (1957) discussed a lode deposit containing uranium in the nearby Ear Mountain pluton. The primary uranium mineral was not identified but a secondary mineral described as intermediate between metazeunerite and metatorbernite was found. The lode deposit was not considered to have economic potential by Killeen and Ordway. Anomalous radioactivity has been reported in the Windy Creek stock (fig. 1) by Sainsbury (1974); the anomaly may be related to a mineralized zone on the west side of the stock or to alkaline subsilicic rocks known to occur in the pluton (Miller and others, 1971). Whether these scattered occurrences of U and Th elsewhere in the Seward Peninsula means the U-Th province extends beyond the area outlined in Clark and others (1972) is uncertain at present.

The Darby pluton has a U and Th content similar to that of the Conway Granite of New Hampshire which has been cited as a low grade U-Th resource (Adams and others, 1962). In addition to whatever potential the Darby pluton might have as a low-grade resource, however, its high U and Th content plus the occurrence of the euxenite-like mineral in the pan concentrates of some streams draining the northeastern part of the pluton suggest the possibility of local concentrations of U and Th which could have more immediate economic potential. The Darby pluton is therefore a favorable area for future exploration.

References Cited

Adams, J. A. S., Kline, M. C., Richardson, K. A., and Rogers, J. J. W., 1962, The Conway Granite of New Hampshire as a major low-grade thorium resource: Natl. Acad. Sci. Proc., v. 48, p. 1898-1905.

Alaska Div. of Geological and Geophysical Surveys, 1973a, Aeromagnetic map, Northern part of Solomon quadrangle, Alaska: Alaska Div. of Geol. and Geophys. Surveys open-file report no. 6, 1 sheet, scale 1:250,000.

______________ 1973b, Aeromagnetic map, Bendeleben quadrangle, Alaska: Alaska Div. Geol. and Geophys. Surveys open-file report no. 3, 1 sheet, scale 1:250,000.

Bunker, C. M., and Bush, C. A., 1966, Uranium, thorium, and radium analyses by gamma-ray spectrometry (0.184-0.352 million electron volts) *in* Geological Survey Research 1966: U. S. Geol. Survey Prof. Paper 550-B, p. B176-B181.

______________ 1967, A comparison of potassium analyses by gamma-ray spectrometry and other techniques: U. S. Geol. Survey Prof. Paper 575-B, p. B164-B169.

Chinner, G. A., 1960, Pelitic gneisses with varying ferrous/ferric ratios from Glen Cova, Angus, Scotland: J. Petrol., v. 1, p. 178-217.

Clark, A. L., Berg, H. C., Cobb, E. H., Eberlein, G. D., MacKevett, E. M., Jr., and Miller, T. P., 1972, Metal provinces of Alaska: U. S. Geol. Survey open-file report, 3 p.

Csejtey, Bela, Jr., and Patton, W. W., Jr., 1974, Petrology of the nepheline syenite of St. Lawrence Island, Alaska: Jour. Research U. S. Geol. Survey, v. 2, no. 1, p. 41-47.

Csejtey, B., Jr., Patton, W. W., Jr., and Miller, T. P., 1971, Cretaceous plutonic rocks of St. Lawrence Island, Alaska: A preliminary report, *in* Geol. Survey Research 1971: U. S. Geol. Survey Prof. Paper 750-D, p. D68-D76.

Dodge, F. C. W., 1972, Trace-element contents of some plutonic rocks of the Sierra Nevada batholith: U. S. Geol. Survey Bull. 1314-F, 13 p.

Gault, H. R., Killeen, P. L., West, W. S., and others, 1953, Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945-47 and 1951: U. S. Geol. Survey Circ. 250, 31 p.

Hopkins, D. M., 1963, Geology of the Imuruk Lake area, Seward Peninsula, Alaska: U. S. Geol. Survey Bull. 1141-C, 101 p.

Killeen, P. L., and Ordway, R. J., 1955, Radioactivity investigations at Ear Mountain, Seward Peninsula, Alaska: U. S. Geol. Survey Bull. 1024-C, 36 p.

Mackin, J. H., and Schmidt, D. L., 1956, Uranium- and thorium-bearing minerals in placer deposits in Idaho, *in* Page, L. R., Stocking, H. E., and Smith, H. B., compilers, 1956, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955: U. S. Geol. Survey Prof. Paper 300, p. 375-380.

Mendenhall, W. C., 1901, A reconnaissance in the Norton Bay Region, Alaska in 1900, pp. 181-222, *in* Brooks, A. H., Richardson, G. B., Collier, A. J., and Mendenhall, W. C., Reconnaissance in Cape Nome and Norton Bay regions, Alaska, Spec. Publ. U. S. Geol. Survey, 222 p.

Miller, T. P., 1970a, Preliminary correlation of Mesozoic plutonic rocks in Bering Sea region: Bull. Amer. Assoc. Petrol. Geol., v. 54, n. 12, p. 2496 (abs.).

____________1970b, Petrology of the plutonic rocks of west-central Alaska: U. S. Geol. Survey open-file report, 132 p.

____________1972, Potassium-rich alkaline intrusive rocks of western Alaska: Geol. Soc. America Bull., v. 83, p. 2111-2128.

Miller, T. P., and Bunker, C. M., 1975, U, Th, and K analyses of selected plutonic rocks from west-central Alaska: U. S. Geol. Survey open-file report # 75-216, 5 p.

Miller, T. P., Elliott, R. L., Grybeck, D. G., and Hudson, T. L., 1971, Results of geochemical sampling in the northern Darby Mountains, Seward Peninsula, Alaska: U. S. Geol. Survey open-file report, p. 12.

Miller, T. P., Grybeck, D. G., Elliott, R. L., and Hudson, T. L., 1972, Preliminary geologic map of the eastern Solomon and southeastern Bendeleben quadrangles, Eastern Seward Peninsula, Alaska: U. S. Geol. Survey open-file report.

Miller, T. P., and Grybeck, D. G., 1973, Geochemical survey of the eastern Solomon and southeastern Bendeleben quadrangles, Seward Peninsula, Alaska: U. S. Geol. Survey open-file report, 115 p.

Moxham, R. M., and West, W. S., 1953, Radioactivity investigations in the Serpentine-Kougarok area, Seward Peninsula, Alaska: U. S. Geol. Survey Circ. 265, 11 p.

Rodgers, J. J. W., and Adams, J. A. S., 1969, Handbook of geochemistry, Vol. 11, Chap. 90 and 92, K. H. Wedepohl, ed., Springer-Verlay Berlin.

Sainsbury, C. L., 1969a, Geology and ore deposits of the Central York Mountains, western Seward Peninsula, Alaska: U. S. Geol. Survey Bull. 1287, 101 p.

__________1969b, The A. J. Collier thrust belt of the Seward Peninsula: Geol. Soc. America Bull., v. 80, no. 12, p. 2595-2596.

__________1974, Geologic map of the Bendeleben quadrangle, Seward Peninsula, Alaska: The Mapmakers, Anchorage, Alaska,31 p.

Sainsbury, C. L., Hudson, T. L., Kachadoorian, Reuben, and Richards, Thomas, 1970, Geology, mineral deposits, and geochemical and radiometric anomalies, Serpentine Hot Springs area, Seward Peninsula, Alaska: U. S. Geol. Survey Bull. 1312-H, 19 p.

Smith, P. S., and Eakin, H. M., 1911, A geologic reconnaissance in southeastern Seward Peninsula and the Norton Bay-Nulato region, Alaska: U. S. Geol. Survey Bull. 449, 146 p.

Tilling, R. I., and Gottfried, David, 1969, Distribution of thorium, uranium, and potassium in igneous rocks of the Boulder batholith region, Montana, and its bearing on radiogenic heat production and heat flow: U. S. Geol. Survey Prof. Paper 614-E, 29 p.

West, W. S., 1953, Reconnaissance for radioactive deposits in the Darby Mountains, Seward Peninsula, Alaska, 1948: U. S. Geol. Survey Circ. 300, 7 p.

West, W. S., and White, M. G., 1952, The occurrence of zeunerite at Brooks Mountain, Seward Peninsula, Alaska: U. S. Geol. Survey Circ. 214, 7 p.

Wollenberg, H. A., and Smith, A. R., 1968, Radiogeologic studies in the central part of the Sierra Nevada batholith, California: Jour. Geophysical Res., v. 73, no. 4, p. 1481-1495.

Table 1. Chemical compositions of the Darby, Bendeleben, and Kachauik plutons.

	Darby pluton 10 analyses		Bendeleben pluton 6 analyses		Kachauik pluton Granodiorite 2 analyses		Kachauik pluton Monzonite-syenite 7 analyses	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
SiO_2	71.5	68.8-74.1	70.2	68.2-70.7	64.4	64.1-64.8	57.0	54.4-60.1
Al_2O_3	14.6	13.5-15.7	15.6	15.2-16.1	16.2	16.2	17.9	17.0-18.9
Fe_2O_3	1.05	0.66-1.5	0.31	0.2-0.4	1.0	0.9-1.0	1.5	0.8-2.7
FeO	0.97	.60-1.7	1.9	1.6-2.3	2.8	2.8	3.8	3.0-4.6
MgO	0.53	.28-.90	0.64	.58-.83	2.3	2.1-2.4	2.0	1.1-2.8
CaO	1.5	1.1-2.2	2.1	1.8-2.6	3.7	3.1-4.2	5.0	3.8-6.6
Na_2O	3.55	3.1-3.9	3.3	3.0-4.1	3.2	3.0-3.3	3.2	2.3-4.1
K_2O	4.97	4.7-5.4	3.85	2.6-4.4	4.6	4.6	6.6	5.2-8.8
H_2O^+	0.50	.31-.75	0.70	.41-.80	.47	.15-.80	0.94	.66-1.0
H_2O^-	0.15	.08-.23	0.17	.10-.26	.17	.11-.24	0.19	.08-.24
TiO_2	0.24	.14-.37	0.41	.35-.52	.54	.54	0.75	.65-.98
P_2O_5	0.10	.04-.18	0.15	.12-.19	.17	.15-.18	0.36	.23-.44
MnO	.05	.00-.10	.07	.07	.00	.00	0.11	.00-.18
CO_2	.02	.01-.08	.01	.01-.02	.02	.02	.03	.01-.08
Fe_2O_3/FeO	1.08		.16		.36		0.39	

Table 2. K-Ar* age dates of the Darby, Bendeleben, and Kachauik plutons.

	Field No.	Pluton	Mineral	Percent K_2O	Ar^{40}_{rad} (moles/gm)	$\frac{Ar^{40}_{rad}}{Ar^{40}_{total}}$	Calculated Age (millions of years)
1	68AMm280	Bendeleben	biotite	8.14	9.799×10^{-10}	0.82	79.8 ± 2.4
2	68AMm285	Darby	biotite	8.93 8.96 } 8.94	1.247×10^{-9}	0.73	92.1 ± 2.8
3	71AMm415A	Darby	biotite	8.96	1.275×10^{-9}	0.78	94.0 ± 3
4	70AMm158B	Darby	hornblende	.893 .896	1.250×10^{-10}	0.81	92.8 ± 2.6
5	70AMm158B	Darby	biotite	7.74 7.87	1.042×10^{-9}	0.93	88.3 ± 1.5
6	70AMm150	Kachauik	hornblende	1.583 1.590 } 1.586	2.346×10^{-10}	0.89	97.5 ± 3

Specimen locations

(1) lat.65°16'N., long. 162°55'W.

(2) lat.65°01'N., long. 162°11'W.

(3) lat.64°57'N., long.162°20'W.

(4) lat.64°45.2'N., long.162°25.2'W.

(5) lat.64°45.2'N., long.162°25.2'W.

(6) lat.64°34'N., long. 162°45'W.

* Ages were caluculated using the following constants: K^{40} decay constants: $\lambda\varepsilon = 0.585 \times 10^{-10} yr^{-1}$, $\lambda\beta = 4.72 \times 10^{-10} yr^{-1}$; abundance ratio: $K^{40}/K = 1.19 \times 10^{-4}$ atom percent. Potassium analyses were done by L. Schlocker by flame photometry using a lithium internal standard. Argon measurements using standard isotope dilution techniques were made by J. Von Essen on samples 1,2, and 6, by J. Von Essen and L. Alba on samples 3, and by J. Von Essen and S. J. Kover on samples 4 and 5.

Table 3. Radioactivity parameters for some southeast Seward Peninsula plutons.
Sample locations shown on Figure 1.

Map No.	Field No.	U ppm	Th ppm	K %	Heat µcal/g yr	Th/U	U/Kx10^-4	Th/Kx10^-4
				Bendeleben pluton				
B1	70AMm59	4.07	15.63	3.34	7.00	3.84	1.22	4.68
B2	70AMm60	3.84	21.37	3.80	8.10	5.57	1.01	5.62
B3	70AEr66	4.38	17.69	3.35	7.64	4.04	1.31	5.28
B4	70AMm70A	9.49	50.84	3.51	18.04	5.36	2.70	14.48
B5	68AMm28	1.82	16.89	3.48	5.65	9.28	0.52	4.85
B6	70AMm67	2.68	11.69	2.21	4.89	4.36	1.21	5.29
Avg.		4.38(3.36)*	22.35(16.7)*	3.28(3.24)*	8.6(6.7)*	5.4(4.63)*	1.33(1.05)	6.7(5.14)
Range		1.82-9.49	11.69-50.84	2.21-3.80	4.89-18.04	3.84-9.28	0.52-2.70	4.85-14.48
				Derby pluton				
D1	68AMm276	7.92	55.15	4.31	17.98	6.96	1.84	12.80
D2	71AMm409	10.29	51.92	3.86	18.94	5.05	2.67	13.45
D3	70AMm212	19.89	83.75	4.08	32.37	4.21	4.88	20.53
D4	71AMm421	17.73	68.80	3.73	27.71	3.88	4.75	18.45
D5	70AMm186A	10.36	64.65	3.72	21.50	6.24	2.78	17.38
D6	70AMm160B	13.50	50.76	4.19	21.24	3.76	3.22	12.11
D7	70AMm160A	8.81	48.77	4.54	17.41	5.54	1.94	10.74
D8	70AMm161	6.18	54.89	4.39	16.67	8.88	1.41	12.50
D9	70AMm159B	7.02	55.16	4.23	17.30	7.86	1.66	13.04
D10	70AMm146	11.71	66.58	4.11	22.97	5.69	2.85	16.20
D11	70AMm145	8.33	68.58	4.02	20.88	8.23	2.07	17.06
D12	70AMm210	9.32	40.84	3.99	16.05	4.38	2.34	10.24
D13	70AMm225	14.61	52.92	3.92	22.31	3.62	3.73	13.50
Avg.		11.2	58.7	4.08	21.0	5.2	2.78	14.46
Range		6.18-19.89	40.84-83.75	3.72-4.54	16.05-32.37	3.62-8.88	1.41-4.88	10.24-20.53
				Kachauk pluton				
				Granodiorite				
K1	71AMm546	4.86	36.07	3.76	11.78	7.42	1.29	9.59
K2	71AMm549	12.46	34.25	3.71	16.95	2.75	3.36	9.23
K3	71AMm545	4.41	10.68	4.17	6.48	2.42	1.06	2.56
K4	70AMm130	6.10	13.59	2.82	7.93	2.23	2.16	4.82
K5	70AMm236	4.33	18.63	3.03	7.70	4.30	1.43	6.15
Avg.		6.4	23.4	4.15	10.17	3.82	1.86	6.47
Range		4.33-12.46	10.68-36.07	2.82-4.17	6.48-16.95	2.23-7.42	1.06-3.36	2.56-9.59
				Monzonite-syenite				
K6	71AMm552	3.58	18.05	5.38	7.68	5.04	0.67	3.36
K7	70AMm135	5.46	29.24	4.37	11.01	5.36	1.25	6.69
K8	70AMm143	3.96	17.68	5.82	8.00	4.46	0.68	3.04
K9	71AMm602	8.74	22.66	4.83	12.22	2.59	1.81	4.69
K10	70AMm141	5.14	20.58	5.54	9.36	4.00	0.93	3.71
K11	70AMm151	1.97	11.26	7.35	5.67	5.72	0.27	1.53
K12	70AMm229	8.62	39.15	5.71	15.66	4.54	1.51	6.86
Avg.		5.2	21.9	5.25	9.94	4.53	1.02	4.27
Range		1.97-8.74	11.26-39.15	4.37-7.35	5.67-15.66	2.59-5.72	0.27-1.93	1.53-6.86

*Sample B4 excluded

Analyses by C.M. Bunker and C.A. Bush

Figure 1. Index map of Alaska showing area of report

Detailed map of area shown on following page (Figure 1. continued)

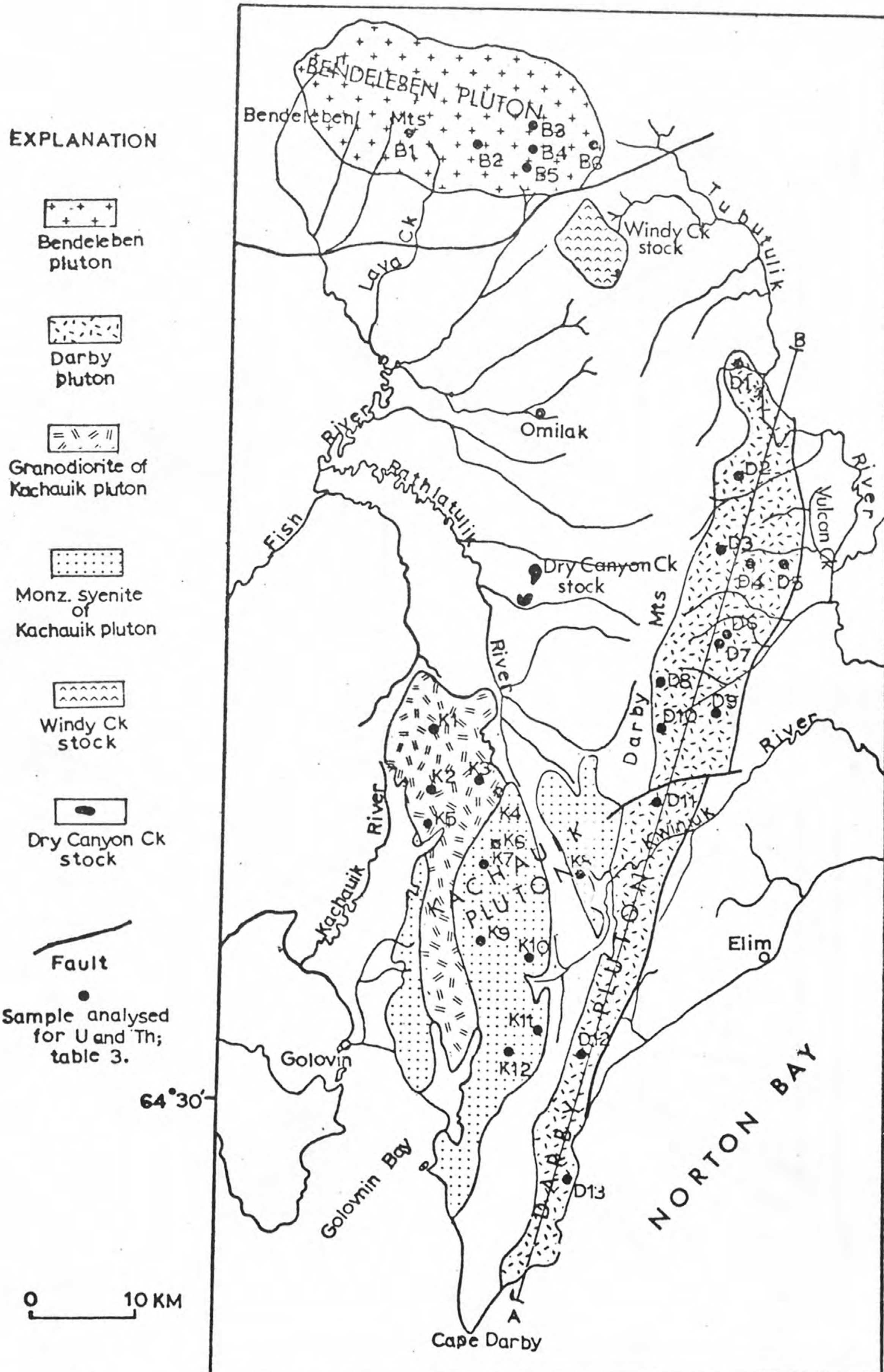

Figure 1. Distribution of plutonic rocks in southeastern Seward Peninsula.

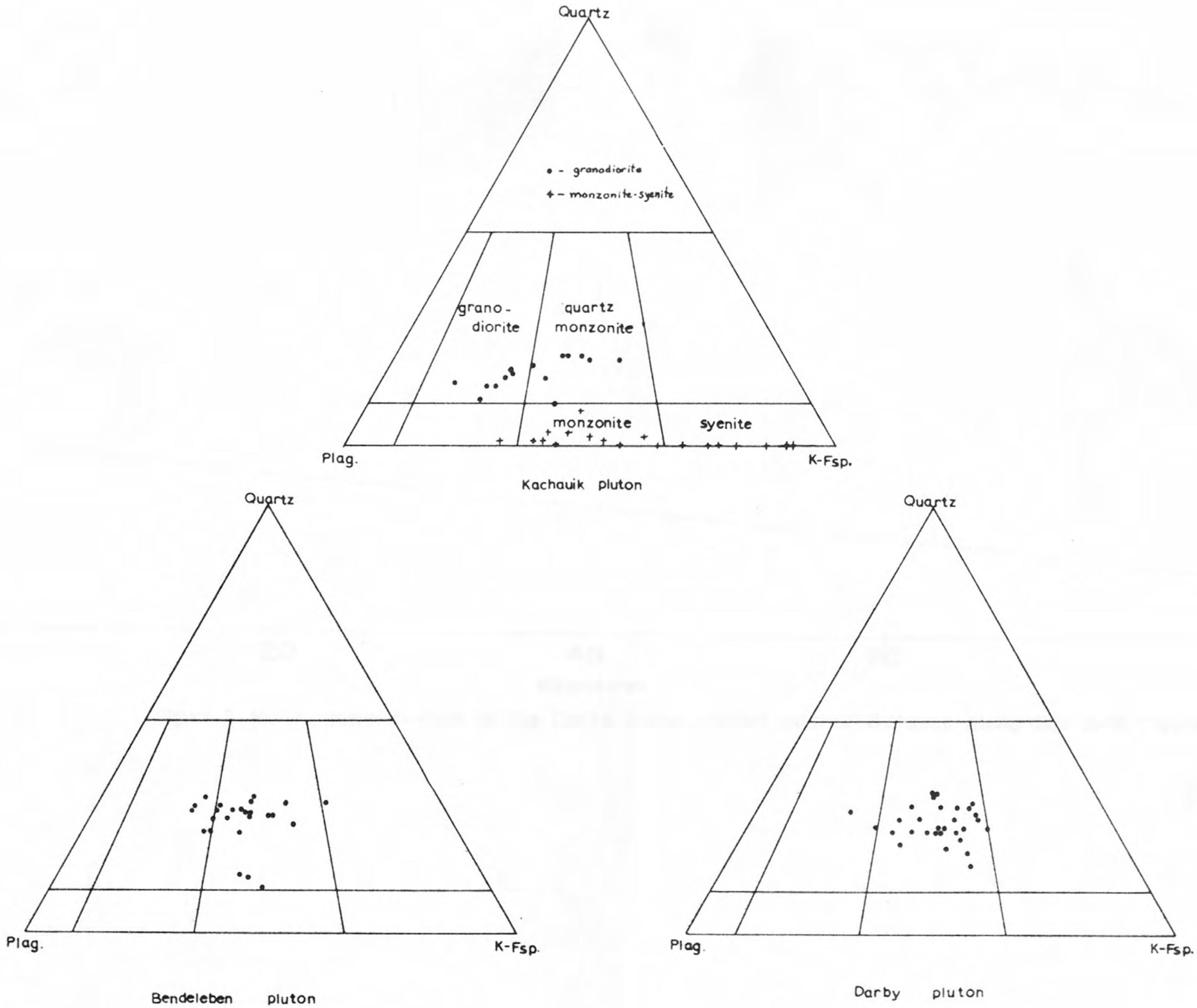

Figure 2. Modal plot of plutonic rocks of southeastern Seward Peninsula.

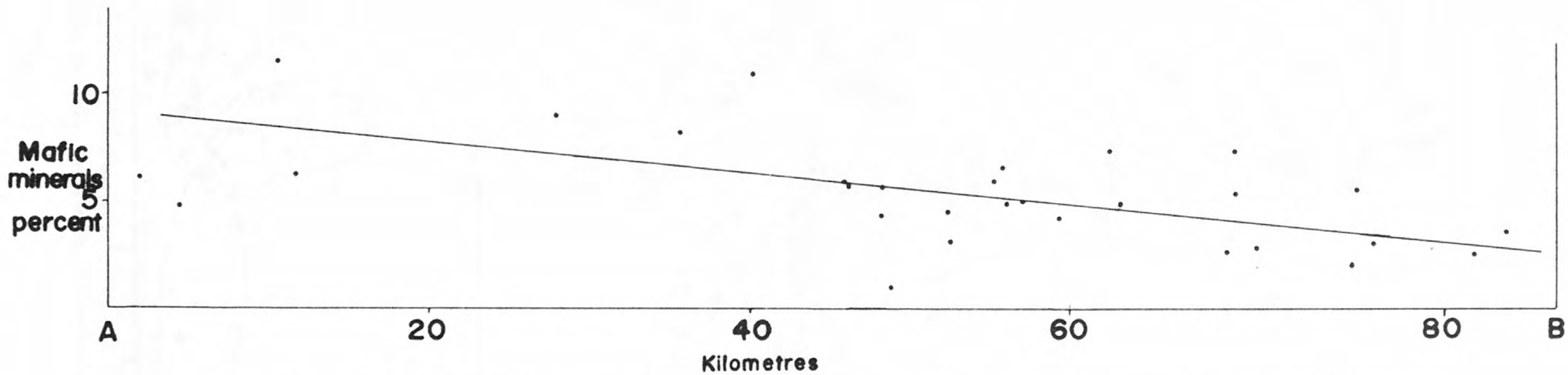

Figure 3. Mafic mineral content of the Darby pluton plotted against distance along line A-B, Figure 1.

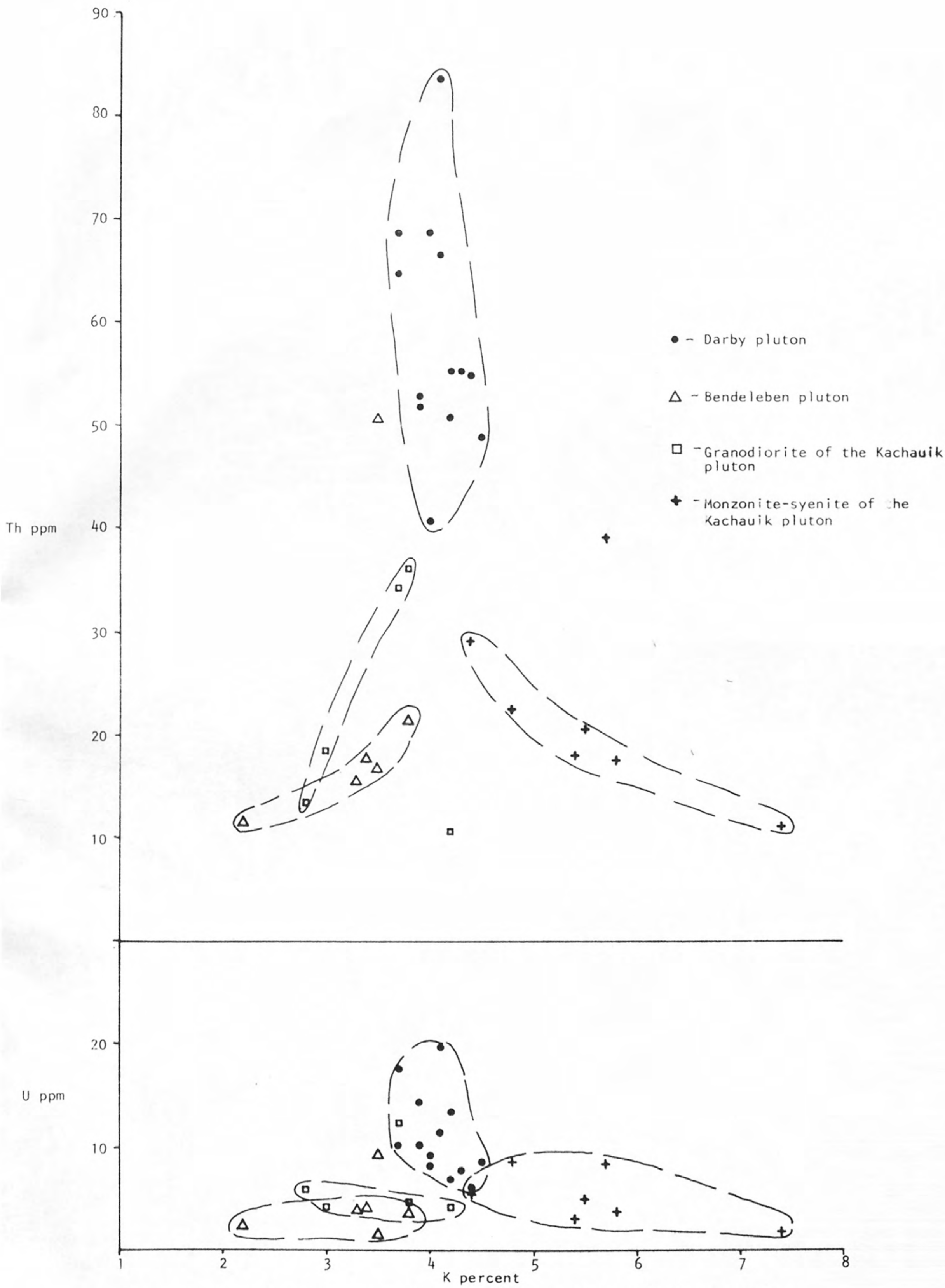

Figure 4. U and Th content of Darby, Bendeleben, and Kachauik plutonic rocks plotted against K.