Shorter Contributions to Isotope Research in the Western United States, 1980

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199 A-E

Shorter Contributions to Isotope Research in the Western United States, 1980

Archean Gneisses in the Little Rocky Mountains, Montana
By ZELL E. PETERMAN

Radioelement Distribution in a 3.06-Kilometer Drill Hole in Precambrian Crystalline Rocks, Wind River Mountains, Wyoming
By CARL M. BUNKER *and* CHARLES A. BUSH

Ages of Igneous Rocks in the South Park–Breckenridge Region, Colorado, and their Relation to the Tectonic History of the Front Range Uplift
By BRUCE BRYANT, RICHARD F. MARVIN,
CHARLES W. NAESER, *and* HARALD H. MEHNERT

Potassium-Argon and Fission-Track Zircon Ages of Cerro Toledo Rhyolite Tephra in the Jemez Mountains, New Mexico
By G. A. IZETT, J. D. OBRADOVICH, C. W. NAESER, *and* G. T. CEBULA

Fission-Track Dating of the Climax and Gold Meadows Stocks, Nye County, Nevada
By C. W. NAESER *and* FLORIAN MALDONADO

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199 A–E

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Doyle G. Frederick, *Acting Director*

Catalog No. 81-600048

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

[Letters designate the chapters]

SYMBOLS AND ABBREVIATIONS USED IN THIS VOLUME

°C	Degrees Celsius
CIPW	Cross, Iddings, Pirsson, and Washington (igneous rock classification system)
cm^2	Square centimeters
g	Grams
IUGS	International Union of Geological Sciences
km	Kilometers
m	Meters
mm	Millimeters
m.y.	Million years
n	Neutrons
ppm	Parts per million
RaeU	Radium-equivalent uranium
yr	Years
λ_f	Decay constant for spontaneous fission of ^{238}U
λ_β	Decay constant based on beta-particle emission
λ_ϵ	Decay constant based on orbital electron capture
μcal/g-yr	Microcalories per gram-year
μm	Micrometers (10^{-6} m)
ρ_i	Induced fission-track density
ρ_s	Spontaneous (fossil) fission-track density
σ	Standard deviation
ϕ	Neutron flux

Archean Gneisses in the Little Rocky Mountains, Montana

By ZELL E. PETERMAN

SHORTER CONTRIBUTIONS TO ISOTOPE RESEARCH
IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199-A

CONTENTS

ILLUSTRATIONS

TABLES

ARCHEAN GNEISSES IN THE LITTLE ROCKY MOUNTAINS, MONTANA

By ZELL E. PETERMAN

ABSTRACT

Rb-Sr dating of a layered complex of tonalitic and granitic gneisses and amphibolite in the Little Rocky Mountains of north-central Montana defines their age as late Archean. Previous K-Ar ages of 1,710 and 1,750 m.y. on hornblende and biotite, respectively, reflect a widespread resetting of K-Ar and Rb-Sr mineral ages in the basement of the Williston basin and of the western Canada sedimentary basin. Although exhibiting some scatter, the Rb-Sr data are consistent with an age of at least 2,550 m.y., and consideration of reasonable initial $^{87}Sr/^{86}Sr$ ratios indicates that the gneisses may be substantially older. Even though the Rb-Sr data do not provide an exact age, an Archean age is firmly established. This age, coupled with determinations on basement cores from southeastern Montana and northeastern Wyoming, extends the Archean terrane of the Wyoming age province well into the buried basement towards the Williston basin. Continuity of the Archean of the Superior province and the Wyoming age province in the subsurface of the Dakotas and eastern Montana remains to be demonstrated, but the gap is narrowed considerably by the data reported here.

INTRODUCTION

The Little Rocky Mountains of north-central Montana are well known for excellent sections of Paleozoic and Mesozoic sedimentary rocks exposed in a domical uplift associated with several Tertiary syenite porphyry stocks (fig. 1). Precambrian rocks are also exposed in the area but as blocks within and marginal to the intrusions. These blocks consist of biotite schist and gneiss, quartzite, and amphibolite that are thought to represent a sequence of sedimentary and volcanic rocks metamorphosed to amphibolite grade (Knechtel, 1959). Hearn and others (1977) report K-Ar ages of 58 to 66 m.y. for the syenite and assign it to the Paleocene. The syenite was locally fractured, silicified, and altered during an episode of mineralization that produced gold-silver deposits in the area.

Burwash, Baadsgaard, and Peterman (1962) determined K-Ar ages of 1,710 and 1,750 m.y. on hornblende and biotite respectively for Precambrian rocks just north of Zortman (fig. 1). These ages are in the common range of K-Ar ages of basement rocks of the western Canada sedimentary basin and of the Williston basin of western north Dakota and eastern Montana. The concordance of the ages from the Little Rocky Mountains suggests that a specific thermal or metamorphic event is being recorded by the K-Ar systems. That these systems were apparently little affected by the Tertiary intrusion is surprising in view of the association of the syenite and the Precambrian rocks. The syenite intrudes Precambrian and possibly Cambrian rocks but is in fault contact with younger rocks (Knechtel, 1959). Considering the relatively small areas of Precambrian rocks, the thermal effects must have been significant but not sufficient to reset the K-Ar systems.

The K-Ar determinations provide a minimum age for the Precambrian rocks of the Little Rocky Mountains and identify them as Precambrian X or older. The nearest Archean rocks crop out in the Little Belt Mountains approximately 200 km southwest of the Little Rocky Mountains; they have been dated by Catanzaro and Kulp (1964), and are part of the major Archean terrane of the Wyoming age province. The extent of Archean rocks in the buried basement of northern and eastern Montana is poorly defined. Gneisses exposed in the Little Rocky Mountains provide indirect access to this otherwise buried basement, and the results obtained from Rb-Sr dating of these gneisses are reported here.

ACKNOWLEDGMENTS

The technical support of G. T. Cebula and J. W. Groen in the careful preparation of the rock samples and of Kiyoto Futa in the analytical work is gratefully acknowledged.

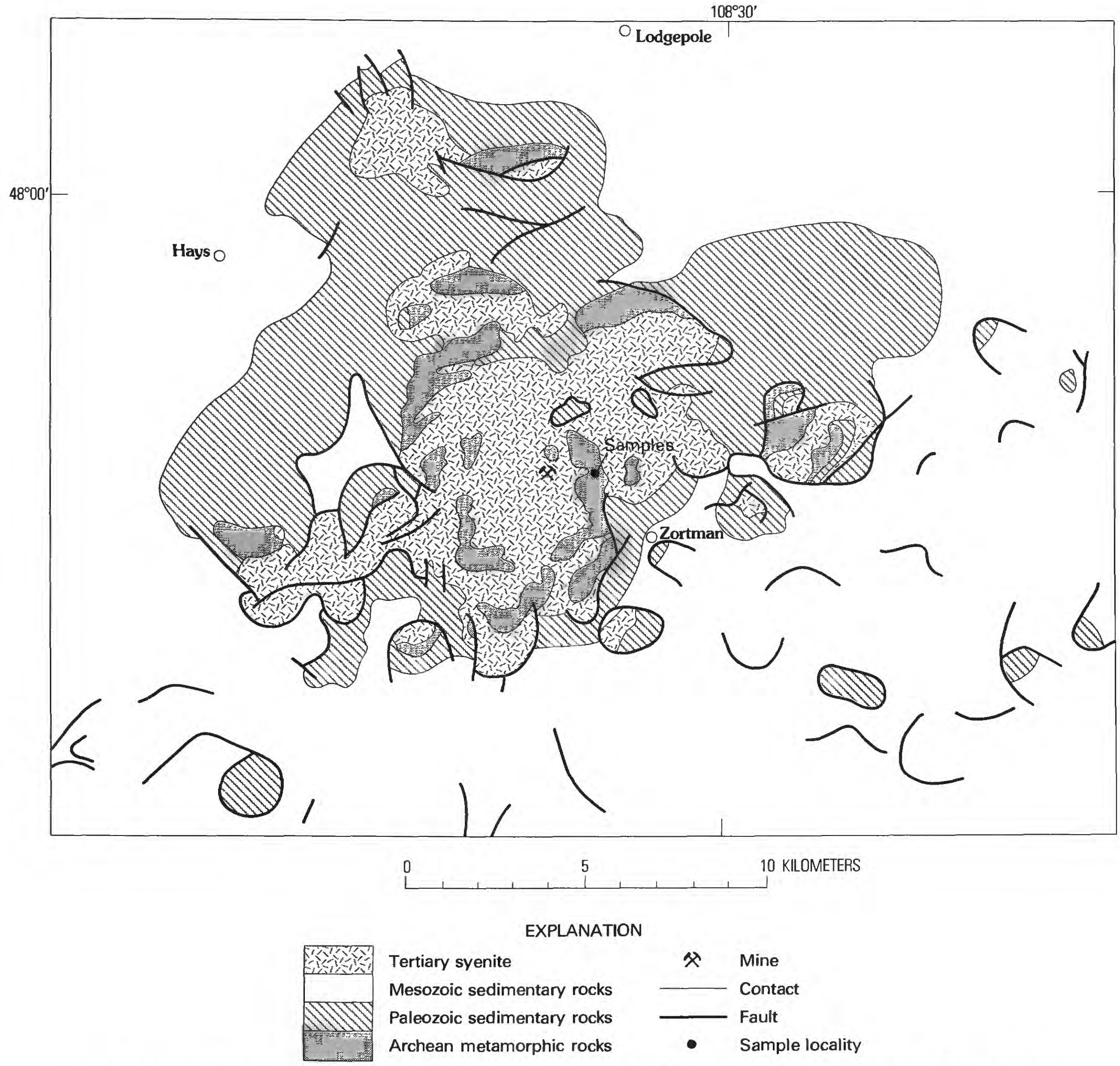


FIGURE 1.—Generalized geology of the Little Rocky Mountains, Montana (adapted from Knechtel, 1959).

SAMPLES AND ANALYTICAL METHODS

Rb and Sr analyses were completed following procedures slightly modified from those described earlier (Peterman and others, 1967). Ages are calculated using the isotopic and decay constants recommended by the International Union of Geological Sciences Subcommission on Geochronology (Steiger and Jager, 1977).

Seven samples were collected from an exposure of Precambrian rocks in a blasted cut along the old haulage road from Zortman to the Ruby Gulch gold mine (fig. 1). A layered complex of gneiss and amphibolite has nearly horizontal banding and foliation at this locality. Fine-grained biotite gneiss is in bands from several centimeters to several tens of centimeters thick. Biotite-hornblende gneiss occurs in layers as much as a meter thick. Amphibolite layers range from a few centimeters to a meter or more, and thinner layers are commonly boudined and tightly folded.

Samples LRM-1, -5, and -6 are light- to medium-gray, fine-grained biotite granite gneiss. A well developed foliation is defined by biotite alinement and by thin (up to 2 mm) lenses of composite quartz.

Quartz, plagioclase, and microcline are present in nearly equal amounts, and biotite forms about 5 percent of the gneiss. Samples LRM-3 and -4 are biotite-hornblende gneiss of tonalitic to granodioritic composition. Poikiloblastic hornblende grains (as much as 2 mm long) are present in fine-grained, well-foliated biotite gneiss with abundant quartz and plagioclase but only sparse microcline. Both samples contain composite augen of quartz, plagioclase, and microcline. LRM-4 contains single plagioclase grains (as much as 3 mm in diameter) that are commonly surrounded by healed mortar structure. Sample LRM-7 is a biotite granite gneiss similar to LRM-1 but with composite augen of quartz and feldspar. LRM-2 is a dark-gray, fine-grained amphibolite with abundant and nearly equal amounts of hornblende and plagioclase, and minor quartz.

Accessory minerals in the amphibolite are sphene, apatite, and altered allanite. The felsic gneisses contain accessory sphene, apatite, zircon, pyrite, magnetite-ilmenite, and altered allanite. Plagioclase **is slightly to moderately sericitized. Biotite is generally fresh with only local chloritization. Hornblende is commonly altered along cleavages. Minor carbonate occurs in most of the samples. Sphene is partially altered to leucoxene on grain margins and along fractures.**

The primary mineral assemblages indicate metamorphism in the amphibolite facies. Some of the alteration may be related to the intrusion of the syenite, but the iron staining is probably due to weathering.

RESULTS

The felsic gneisses have similar Rb and Sr contents (table 1) and, therefore, a limited range in Rb/Sr ratios that precludes clear definition of a Rb-Sr **isochron by these data alone. The amphibolite has a much lower Rb/Sr ratio, and a reference isochron corresponding to an age of 2,550 m.y. is drawn through this point and the points for the felsic gneisses (fig. 2). The points scatter well outside of analytical error, and the data do not warrant a more sophisticated regression. The reference isochron has to be drawn through a relatively high initial $^{87}Sr/^{86}Sr$ ratio of 0.706 in order to accomodate the data point for the amphibolite. Model ages can be calculated for the felsic gneisses using an initial-Sr ratio of 0.071, a value more common for rocks of late Archean age. These model ages range from 2,920 to 2,620 m.y., and the average value of 2,770 m.y. would correspond approximately to an average "wholerock" composite age for the felsic gneisses.**

TABLE 1.—*Rb-Sr analyses of samples of Precambrian rocks from the Little Rocky Mountains, Montana*

[Analyst: Kiyoto Futa]

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{*87}Sr/^{86}Sr$
LRM-1†	124	219	1.655	0.7636
LRM-1†	123	219	1.630	.7635
LRM-2	10.7	269	.116	.7105
LRM-3	114	285	1.159	.7486
LRM-4	98.7	220	1.306	.7563
LRM-5	124	232	1.555	.7617
LRM-6	110	258	1.241	.7516
LRM-7	103	181	1.649	.7660

*Normalized to $^{86}Sr/^{88}Sr$ = 0.1194.
†Duplicate analyses.

Although the Rb-Sr systematics do not provide an especially accurate determination of the age, the data clearly establish the gneisses as Archean. The scatter of data points is not surprising in view of the metamorphic event at 1,700 to 1,800 m.y., the contact effects of the Paleocene syenite, and recent weathering. If the whole-rock Rb-Sr systems have been modified by any or all of these events, the effect would most likely have been to lower the age through loss of radiogenic Sr, gain of Rb, or internal redistribution of both elements. Consequently, the Rb-Sr systematics provide a firm minimum age for the gneisses.

REGIONAL CONSIDERATIONS

Most of the Precambrian of the United States is concealed beneath Phanerozoic cover (see **King, 1976, fig. 1, p. 4–5) and not readily accessible for geologic studies. Significant advances in understanding the Precambrian history of the buried basement have been made through rediometric dating of basement samples obtained in drilling, largely in petroleum exploration. A major dating study of the basement of the U.S. culminated in a series of four reports (Goldich, Lidiak, and others, 1966; Goldich, Muehlberger, and others, 1966; Muehlberger and others, 1966; and Lidiak and others, 1966) followed by a regional synthesis for North America (Muehlberger and others, 1967). Very few ages of basement rocks have been reported since 1966.**

A goal of the dating studies is the delineation of age provinces in the basement. Many of these are subsurface extensions of the geologic and age provinces of the Canadian shield; others appear to be unique to the subsurface. The extent of these provinces, their age and lithologic character, and their mutual relationships are fundamental

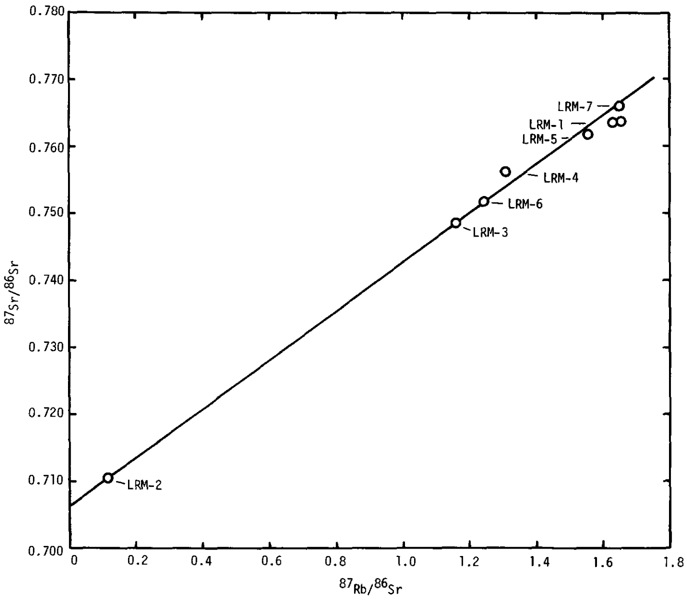


FIGURE 2.—Rb-Sr isochron plot for samples of gneiss and amphibolite from the Little Rocky Mountains, Montana. The slope of the isochron corresponds to an age of 2,550 m.y., and the initial $^{87}Sr/^{86}Sr$ intercept is 0.706.

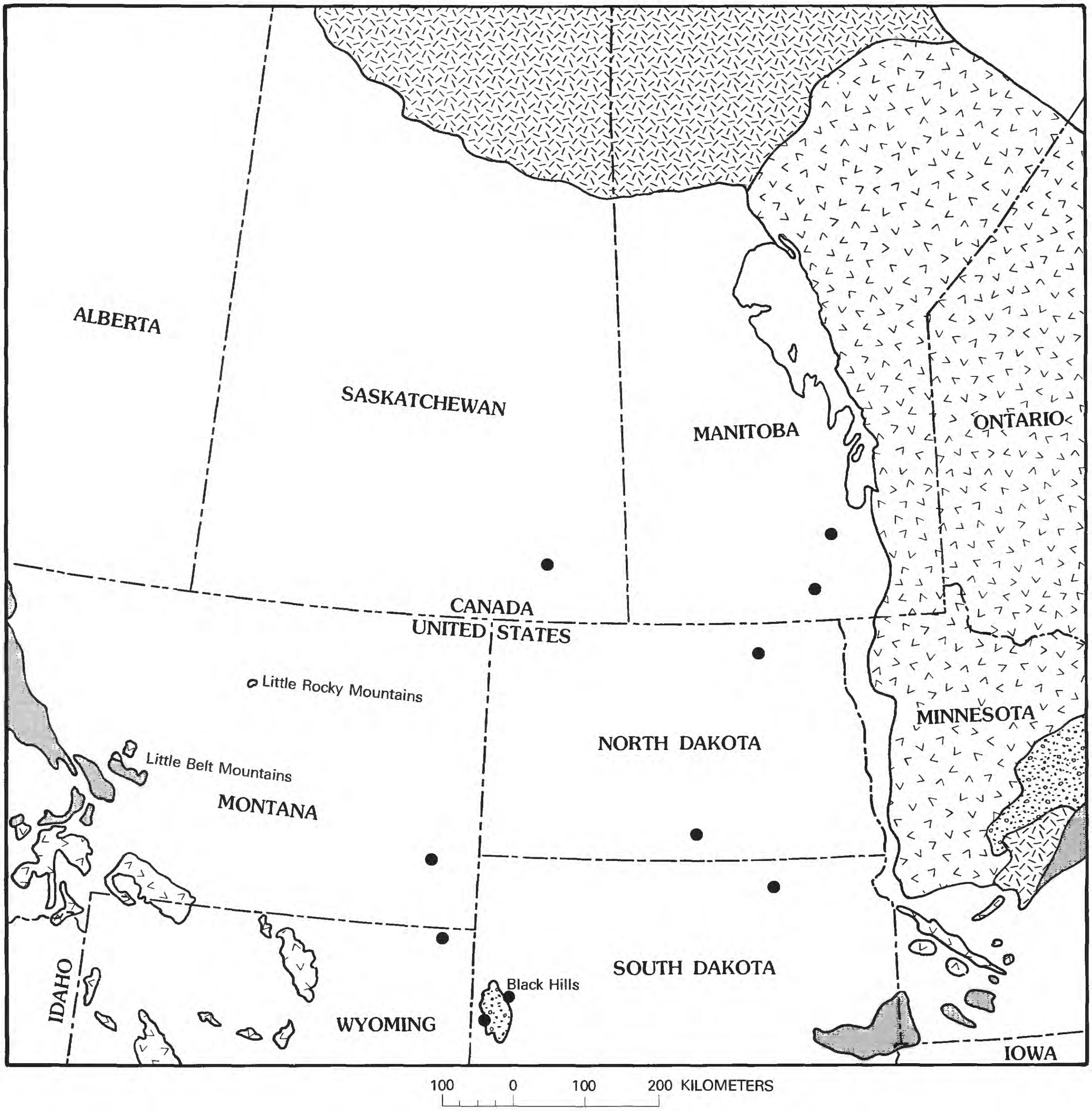
problems that have not been fully resolved in the buried basement nor in many exposed Precambrian terranes for that matter.

The basement of eastern Montana, eastern Wyoming, North Dakota, and South Dakota is of particular interest because it lies between two major exposed Archean terranes: the Wyoming age province on the west and the Superior province on the east (fig. 3). Three major problems are (1) whether or not Archean crust is continuous in the subsurface between the exposed Archean terranes, (2) the extent of lower Proterozoic (Precambrian X) supracrustals in the subsurface, and (3) the nature of the event that produced the 1,600- to 1,800-m.y. K-Ar and Rb-Sr mineral ages and the amount of intrusive rock emplaced during this event. Only a few dated samples from the basement provide clear evidence of Archean rocks (fig. 3). In the eastern Dakotas, proximity to the exposed Archean rocks of Minnesota and Manitoba and geophysical data coupled with basement lithologies provide additional evidence for an Archean basement in this region (Muehlberger and others, 1967; Lidiak, 1971).

In the Black Hills, a key area in the western part of this region (fig. 3), folded and metamorphosed lower Proterozoic supracrustals lie on Archean basement. The deformation and intrusive event in this area between 1,600 and 1,800 m.y. was named the Black Hills orogeny (Goldich, Lidiak, and others, 1966). The Harney Peak Granite associated with this event is dated at 1,710 m.y. (Riley, 1970). Zartman and Stern (1967) established the Little Elk Granite in the northeastern Black Hills as Archean basement. Rb-Sr systems in whole rocks and minerals were reset by cataclasis and recrystallization during the Black Hills orogeny, but the U-Pb systems in zircon retained the Archean age. Archean rocks were also discovered in the western Black Hills, where Ratté and Zartman (1970) obtained 2,500-m.y. ages on granite and pegmatite from the core of a gneiss dome that penetrates supracrustals at Bear Mountain.

The extent of lower Proterozoic supracrustals in the basement to the west and north of the Black Hills is largely conjectural. However, Lidiak (1971), in his construction of a geologic map of the basement of South Dakota, interprets gravity and aeromagnetic anomalies in the central and western part of the state as reflecting 1,600- to 1,800-m.y.-old structural elements that trend north to northwest. On a more regional scale, Camfield and Gough (1977) have delineated a conductive zone in the basement that skirts the east side of the Black Hills and extends north to the Canadian shield and south to the Laramie Range of southeastern Wyoming. The origin of the anomaly is problematic, but Camfield and Gough (1977) note a correspondence or alinement with highly sheared and deformed rocks in both Saskatchewan and southeastern Wyoming, and they suggest that the zone may be a suture related to plate collision in the Proterozoic. The southernmost part of the anomaly is more or less coincident with part of the Colorado lineament described by Warner (1978). Warner presents abundant evidence for a Precambrian wrench-fault system extending from northern Arizona northeasterly to the southwestern tip of Lake Superior and postulates that the fault was approximately marginal to a continental plate in the early Proterozoic.

The present study of the Precambrian of the Little Rocky Mountains does not bear on the extent of the lower Proterozoic in the basement or on the nature of the orogenic event, but it does document an extension of the Archean into north-central Montana. Further evidence for this extension is provided by data for two basement cores obtained in U.S. Geological Survey drill holes that have been dated by the Rb-Sr method (Peterman, unpub. data, 1978). A hole in northeastern Wyoming (fig. 3) penetrated a banded gneiss complex that gives an isochron age of 2,640 m.y. A hole to the north in Montana encountered a porphyritic biotite granite that gives a model Rb-Sr age of approximately 2,800 m.y. These data, coupled with data for the Little Rocky Mountains, extend the Archean basement well into the subsurface towards the Wiliston basin. Whether or not the Archean was continuous between the Wyoming age province and



EXPLANATION

PRECAMBRIAN Y

Belt Supergroup of Montana, Keweenawan Supergroup of Minnesota, and Sioux Quartzite of Minnesota and South Dakota

PRECAMBRIAN X

Penokean granites of Minnesota, and Churchill Province of Canada (in part Archean)

Animikie Group of Minnesota, and metasedimentary and metavolcanic rocks of the Black Hills (including the Harney Peak Granite)

ARCHEAN

Superior Province of Canada and Archean rocks of Minnesota and of the Wyoming age province

Subsurface samples dated as Archean, and two Archean outcrop areas in the Black Hills (the Little Elk Granite and the granite gneiss at Bear Mountain)

FIGURE 3.—Regional Precambrian framework of the north-central United States and adjacent Canada. Adapted from the "Basement Map of North America" (Flawn, 1967). Age data for basement samples are from Burwash and others (1962); Peterman and Hedge (1964); Goldich, Lidiak, and others (1966); Peterman (unpub. data, 1978). Archean ages in the Black Hills are from Zartman and Stern (1967) and Ratté and Zartman (1970).

the Superior province will have to be determined by additional dating of basement samples by methods that are capable of penetrating the effects of the 1,600- to 1,800-m.y. event.

REFERENCES CITED

Burwash, R. A., Baadsgaard, H., and Peterman, Z. E., 1962, Precambrian K-Ar dates from the western Canada sedimentary basin: Journal of Geophysical Research, v. 67, p. 1617-1625.

Camfield, P. A., and Gough, D. I., 1977, A possible Proterozoic plate boundary in North America: Canadian Journal of Earth Sciences., v. 14, p. 1229-1238.

Catanzaro, E. J., and Kulp, J. L., 1964, Discordant zircons from the Little Belt (Montana), Beartooth (Montana) and Santa Catalina (Arizona) Mountains: Geochimica et Cosmochimica Acta, v. 28, p. 87-124.

Flawn, P. T., 1967, Basement map of North America: U.S. Geological Survey.

Goldich, S. S., Lidiak, E. G., Hedge, C. E., and Walthall, F. G., 1966, Geochronology of the midcontinent region, United States, 2., Northern area: Journal of Geophysical Research, v. 71, p. 5389-5408.

Goldich, S. S., Muehlberger, W. R., Lidiak, E. G., and Hedge, C. E., 1966, Geochronology of the midcontinent region, United States, 1., Scope, methods, and principles: Journal of Geophysical Research, v. 71, p. 5375-5388.

Hearn, B. C., Jr., Marvin, R. F., Zartman, R. E., and Naeser, C. W., 1977, Geochronology of igneous activity in the north-central alkalic province (abs.): Geological Society of America Abstracts with Programs, v. 9, no. 6, p. 732.

King, P. B., 1976, Precambrian geology of the United States; an explanatory text to accompany the geologic map of the United States: U.S. Geological Survey Professional Paper 902, 85 p.

Knechtel, M. W., 1959, Stratigraphy of the Little Rocky Mountains and encircling foothills, Montana: U.S. Geological Survey Bulletin 1072-N, p. 723-752.

Lidiak, E. G., 1971, Buried Precambrian rocks of South Dakota: Geological Society of America Bulletin v. 82, p. 1411-1420.

Lidiak, E. G., Marvin, R. F., Thomas, H. H., and Bass, M. N., 1966, Geochronology of the midcontinent region, United States, 4., Eastern region: Journal of Geophysical Research, v. 71, p. 5427-5438.

Muehlberger, W. R., Denison, R. E., and Lidiak, E. G., 1967, Basement rocks in continental interior of United States: American Association of Petroleum Geologists Bulletin, v. 51, p. 2351-2380.

Muehlberger, W. R., Hedge, C. E., Denison, R. E., and Marvin, R. F., 1966, Geochronology of the midcontinent region, United States, 3., Southern area: Journal of Geophysical Research, v. 71, p. 5409-5426.

Peterman, Z. E., and Hedge, C. E., 1964, Age of basement rocks from the Williston basin of North Dakota and adjacent areas, *in* Geological Survey research 1963: U.S. Geological Survey Professional Paper 475-D, p. D100-D104.

Peterman, Z. E., Doe, B. R., and Bartel, Ardith, 1967, Data on the rock GSP-1 (granodiorite) and the isotope-dilution method of analysis for Rb and Sr, *in* Geological Survey research 1967: U.S. Geological Survey Professional Paper 575-B, p. B181-B186.

Ratté, J. C., and Zartman, R. E., 1970, Bear Mountain gneiss dome, Black Hills, South Dakota—Age and structure (abs.): Geological Society of America Abstracts with Programs, v. 2, no. 5, p. 345.

Riley, G. H., 1970, Isotopic discrepancies in zoned pegmatites, Black Hills, South Dakota: Geochimica et Cosmochimica Acta, v. 34, p. 713-725.

Steiger, R. H., and Jager, E., 1977, Subcommission on geochronology—Convention and use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359-362.

Warner, L. A., 1978, The Colorado lineament—A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, p. 161-171.

Zartman, R. E., and Stern, T. W., 1967, Isotopic age and geologic relationships of the Little Elk Granite, northern Black Hills, South Dakota: U.S. Geological Survey Professional Paper 575-D, p. D157-D163.

Radioelement Distribution in a 3.06-Kilometer Drill Hole in Precambrian Crystalline Rocks, Wind River Mountains, Wyoming

By CARL M. BUNKER *and* CHARLES A. BUSH

SHORTER CONTRIBUTIONS TO ISOTOPE RESEARCH
IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199-B

CONTENTS

ILLUSTRATIONS

TABLES

RADIOELEMENT DISTRIBUTION IN A 3.06-KILOMETER DRILL HOLE IN PRECAMBRIAN CRYSTALLINE ROCKS, WIND RIVER MOUNTAINS, WYOMING

By C. M. BUNKER and C. A. BUSH

ABSTRACT

Uranium, thorium, and potassium contents were measured in 229 samples of cuttings from a drill hole that penetrates 3.06 kilometers of Precambrian crystalline rock on the southwestern flank of the Wind River Mountains, Wyoming. Thorium and potassium contents are similar to reported averages for intermediate to silicic igneous rock, and uranium content is in the range of averages for mafic to intermediate rock; these data indicate that the rock is deficient in uranium. The radioelement data support geologic and geophysical data which indicate that the drill hole penetrates a thick section of layered, fractured, heterogeneous rock.

INTRODUCTION

A 3.06-kilometer exploratory borehole was drilled into Precambrian crystalline rocks on the southwestern flank of the Wind River Mountains, Wyoming, to obtain geologic and geophysical data. The hole is in sec. 2, T. 32 N., R. 197 W. (lat 42°45′30″ N., long 109°31′30″ W.) about 23 km southeast of Pinedale, Wyo.; the collar elevation is 2219 m above mean sea level (fig. 4).

The Wind River Mountains are a broad asymmetrical anticline exposing Precambrian crystalline rocks in the core. Several kilometers of rock may have been eroded above the existing surface at the drill-hole site. The flank of the Wind River Mountains overthrusts the Green River Basin to the southwest; the thrust dips gently to the northeast. Rocks exposed at the surface near the drill hole and all core samples show nearly horizontal foliation.

Petrographic descriptions of cores taken from depths 50 to 300 m apart have been reported by Ebens and Smithson (1966). The rock cores are granitic (quartzo-feldspathic) in general character, but they are very heterogeneous. Composition ranges from quartz-dioritic to granodioritic to quartz-monzonitic gneiss; texture ranges from fine grained to porphyroblastic. Neither composition nor texture shows any relationship to depth, although the mineralogy suggests an increase in grade of metamorphism with depth. Ebens and Smithson (1966) concluded that the hole penetrates a heterogeneous layered sequence of metamorphic rocks.

A seismic velocity survey and sonic, caliper, and neutron logs of the drill hole indicate that the rock is fractured throughout the depth of the hole (Smithson and Ebens, 1971). The fracturing is very likely related to the proximity of the drill hole to the thrust fault. A major fracture zone with cracks exists to a depth of 460 m; a sharp increase in velocity at that depth is interpreted as being related to the absence of cracks below that depth. Other highly fractured zones are indicated at 1,642 m and from 2,665 to at least 2,700 m. Relatively unfractured zones occur from about 2,000 to 2,650 m, which is also a zone of relatively high rock density, and from 2,865 to 2,890 m. A gamma-ray log of the hole shows general changes in radiation intensity which are probably

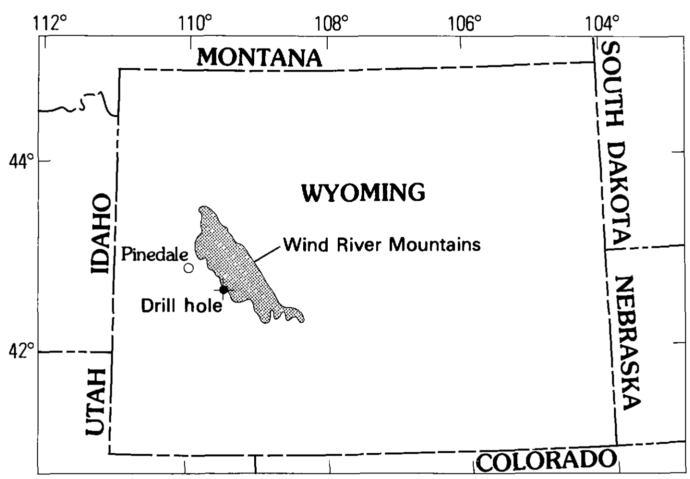


FIGURE 4.—Location of 3.06-kilometer-deep drill hole in the Wind River Mountains, Wyoming.

related to changes in rock type. The gamma-ray log also shows many zones ranging in thickness from about 0.3 to 15 m in which the radioelement content is greater than that of the host rock. These relatively thin zones of anomalous radioactivity are not apparently related to anomalies on the neutron log; however, the radioactivity anomalies can be interpreted as indications of either mineralogic differences in the host rock or enrichment of radioelement contents in at least some of the fracture zones. These geophysical data confirm that the rock is heterogeneous both in composition and physical properties, as was previously determined from a few core samples.

In addition to the 19 cores that were obtained, drill cuttings were collected from virtually the entire depth of the hole. Ninety-nine of these samples were used for measurements of radiogenic heat production (Lachenbruch and Bunker, 1971); those plus an additional 130 samples were used in the present investigation. Most of the samples represent about 3 m of rock penetrated by the drill hole; a few represent 1.5-m intervals. The distance between samples range from 0 to 36 m, but most of the sampled intervals are 3.3 to 9.8 m apart.

The principal objective of the radioelement analyses was to determine the distribution of uranium, thorium, potassium, and the associated radiogenic heat through a thick vertical section of Precambrian crystalline rocks. We also plan to compare these data with radioelement analyses of Precambrian granites in central Wyoming.

ANALYTICAL METHOD

Radioelement (K, RaeU, and Th) contents of the samples were measured by gamma-ray spectrometry. Approximately 600 g of the material were sealed in 15-cm-diameter plastic containers. The containers were placed on a sodium iodide crystal 12.5 cm in diameter and 10 cm thick. The gamma radiation penetrating the crystal was sorted according to energy by the associated electronic devices, and the resulting spectra were stored in a 512-channel memory. The spectra were interpreted with the aid of a linear-least-squares computer method which matches the spectrum from a sample to a library of radioelement standards; the computer method for determining concentrations is a modification of a program written by Schonfeld (1966). Standards used to reduce the data include the USGS standard rocks, New Brunswick Laboratories standards, and several samples for which uranium and thorium concentrations have been determined by isotope dilution and mass or alpha spectrometry.

Uranium contents were measured indirectly by measuring the ^{226}Ra daughters (^{214}Bi and ^{214}Pb) to obtain radium-equivalent uranium (RaeU) values. Radium-equivalent uranium is the amount of uranium required for secular isotopic equilibrium with the ^{226}Ra and its daughters measured in a sample. Isotopic equilibrium between these daughters and ^{226}Ra was accomplished by allowing the sealed sample containers to sit for at least 21 days prior to the analyses. All uranium concentrations measured in the drill-hole samples are radium-equivalent values.

Although thorium is also measured from daughter products (^{212}Bi, ^{212}Pb, and ^{208}Tl), isotopic disequilibrium is improbable because the daughter products measured have such short half-lives that their concentration directly reflects that of thorium. Potassium is determined from the ^{40}K isotope, which is radioactive and directly proportional to the total potassium.

All the radioelement data (table 2) reported in this paper are based on replicate analyses. The coefficient of variation for the accuracy of these data, when compared to isotope-dilution and flame-photometry analyses, is about ±2 percent for RaeU and Th and about ±1 percent for K. These percentages are in addition to minimum standard deviations of about 0.05 ppm for RaeU and Th and 0.03 percent for K.

RESULTS

The highly variable character of the distribution of the radioelement contents and ratios in the rock penetrated by the drill hole (fig. 5) reflects the layering, fracturing, and heterogeneity in mineral content and rock types that were observed by examination of core samples or interpreted from geophysical logs. An exception to the highly variable radioelement distribution is the depth interval from about 2,040 to 2,650 m, in which the uranium and potassium contents are nearly constant, thereby indicating a fairly homogenous layer of rock. This is a relatively unfractured zone in which the transport and redistribution of radioelements is less likely than in the highly fractured zones. We believe that the measured radioelement contents in the 2,040- to 2,650-m interval are the intrinsic values of the rock, which has been described as foliated porphyroblastic quartz monzonite (Ebens and Smithson, 1966).

TABLE 2.—*Summary of radioelement and radiogenic heat analyses on 229 core samples from a drill hole in Wind River Mountains, Wyoming*

Sample depth (meters)	RaeU (ppm)	Th (ppm)	K (percent)	Heat (μcal/g-yr)	Th/RaeU	RaeU/K$\times 10^{-4}$	Th/K$\times 10^{-4}$
6.1- 9.1	0.42	5.95	4.94	2.83	14.17	0.09	1.20
18.3- 21.3	0.84	15.60	3.45	4.66	18.57	0.24	4.52
36.6- 39.6	1.19	28.53	3.92	7.63	23.97	0.30	7.28
45.7- 48.8	1.15	18.04	4.09	5.55	15.69	0.28	4.41
51.8- 54.9	1.07	21.32	3.77	6.06	19.93	0.28	5.66
61.0- 64.0	2.23	24.09	3.62	7.42	10.80	0.62	6.65
67.1- 70.1	1.15	15.78	4.31	5.16	13.72	0.27	3.66
76.2- 79.2	1.16	78.27	5.23	17.91	6 .47	0.22	14.97
85.3- 88.4	1.74	72.18	4.53	16.93	41.48	0.38	15.93
97.5- 100.6	1.78	52.11	4.76	13.01	29.28	0.37	10.95
106.7- 109.7	1.50	43.32	4.35	10.93	28.88	0.34	9.96
112.8- 115.8	1.25	32.91	4.56	8.73	26.33	0.27	7.22
121.9- 125.0	1.40	30.98	4.11	8.33	22.13	0.34	7.54
131.1- 134.1	0.90	28.69	3.81	7.42	31.88	0.24	7.53
140.2- 143.3	1.43	34.90	3.64	9.01	24.41	0.39	9.59
152.4- 155.4	1.06	8.10	3.55	3.35	7.64	0.30	2.28
161.5- 164.6	1.84	9.29	2.38	3.84	5.05	0.77	3.90
167.6- 170.7	2.06	9.68	1.67	3.89	4.70	1.23	5.80
176.8- 179.8	1.31	9.38	3.40	3.75	7.16	0.39	2.76
185.9- 189.0	1.48	15.95	2.52	4.95	10.78	0.59	6.33
204.2- 207.3	2.70	19.60	3.43	6.82	7.26	0.79	5.71
213.4- 216.4	2.56	17.85	3.26	6.32	6.97	0.79	5.48
222.5- 225.6	2.13	12.74	2.75	4.85	5.98	0.77	4.63
231.6- 234.7	2.02	21.81	3.58	6.80	10.80	0.56	6.09
240.8- 243.8	1.76	27.26	3.42	7.66	15.49	0.51	7.97
249.9- 253.0	5.04	21.58	3.16	8.85	4.28	1.59	6.83
259.1- 262.1	12.94	33.24	2.79	16.85	2.57	4.64	11.91
268.2- 271.3	3.17	21.84	2.64	7.39	6.89	1.20	8.27
277.4- 280.4	2.88	26.78	3.55	8.42	9.30	0.81	7.54
283.5- 286.5	1.55	12.62	4.82	4.96	8.14	0.32	2.62
289.6- 292.6	3.29	31.25	3.60	9.62	9.50	0.91	8.68
295.7- 298.7	2.74	21.48	3.29	7.18	7.84	0.83	6.53
304.8- 307.8	3.87	11.96	2.78	5.97	3.09	1.39	4.30
313.9- 317.0	2.48	10.41	2.19	4.48	4.20	1.13	4.75
320.0- 323.1	3.81	14.20	2.66	6.34	3.73	1.43	5.34
329.2- 332.2	2.09	10.76	2.03	4.23	5.15	1.03	5.30
338.3- 341.4	2.71	20.28	3.60	7.01	7.48	0.75	5.63
344.4- 347.5	2.62	21.79	3.73	7.28	8.32	0.70	5.84
350.5- 353.6	2.25	19.87	3.11	6.46	8.83	0.72	6.39
359.7- 362.7	2.83	19.03	3.07	6.70	6.72	0.92	6.20
368.8- 371.9	3.64	21.72	3.27	7.88	5.97	1.11	6.64
381.0- 384.0	2.96	15.82	2.81	6.08	5.34	1.05	5.63
387.1- 390.1	2.29	13.86	2.13	5.02	6.05	1.08	6.51
396.2- 399.3	2.62	16.82	2.85	6.05	6.42	0.92	5.90
405.4- 408.4	2.27	16.12	3.32	5.78	7.10	0.68	4.86
414.5- 417.6	2.35	16.57	2.98	5.83	7.05	0.79	5.56
423.7- 426.7	2.57	18.00	2.86	6.25	7.00	0.90	6.29
432.8- 435.9	2.22	16.00	3.05	5.64	7.21	0.73	5.25
442.0- 445.0	3.73	20.54	3.69	7.83	5.51	1.01	5.57
448.1- 451.1	2.37	16.04	3.55	5.90	6.77	0.67	4.52
454.2- 457.2	2.19	16.74	3.69	5.94	7.64	0.59	4.54
460.2- 463.3	1.95	14.99	3.26	5.30	7.69	0.60	4.60
493.8- 496.8	2.15	16.06	3.31	5.68	7.47	0.65	4.85
521.2- 524.3	1.81	14.04	3.31	5.02	7.76	0.55	4.24
545.6- 548.6	1.30	7.47	2.78	3.19	5.75	0.47	2.69
554.7- 557.8	1.72	11.88	3.10	4.47	6.91	0.55	3.83
579.1- 582.2	2.23	9.32	1.99	4.03	4.18	1.12	4.68
591.3- 594.4	1.52	8.04	2.73	3.45	5.29	0.56	2.95
597.4- 600.5	2.45	21.73	3.29	7.02	8.87	0.74	6.60
609.6- 612.6	1.38	10.19	2.86	3.82	7.38	0.48	3.56
618.7- 621.8	2.18	16.90	2.71	5.70	7.75	0.80	6.24
624.8- 627.9	2.48	26.14	3.95	8.10	10.54	0.63	6.62
634.0- 637.0	3.00	20.06	3.42	7.13	6.69	0.88	5.87
646.2- 649.2	1.80	10.59	3.41	4.35	5.88	0.53	3.11
658.4- 661.4	1.41	11.00	3.00	4.04	7.80	0.47	3.67

TABLE 2.—*Summary of radioelement and radiogenic heat analyses on 229 core samples from a drill hole in Wind River Mountains, Wyoming—Continued*

Sample depth (meters)	RaeU (ppm)	Th (ppm)	K (percent)	Heat (μcal/g-yr)	Th/RaeU	RaeU/K$\times 10^{-4}$	Th/K$\times 10^{-4}$
664.5- 667.5	1.98	13.87	2.96	5.02	7.01	0.67	4.69
679.7- 682.8	2.02	17.96	3.64	6.05	8.89	0.55	4.93
685.8- 688.8	2.04	24.75	3.58	7.41	12.13	0.57	6.91
694.9- 698.0	2.39	24.37	3.82	7.65	10.20	0.63	6.38
701.0- 704.1	2.09	21.62	3.61	6.82	10.34	0.58	5.99
713.2- 716.3	1.96	10.92	3.12	4.46	5.57	0.63	3.50
728.5- 731.5	1.86	20.57	3.59	6.44	11.06	0.52	5.73
740.7- 743.7	1.57	11.05	2.62	4.06	7.04	0.60	4.22
752.9- 755.9	1.59	20.86	3.45	6.26	13.12	0.46	6.05
759.0- 762.0	1.75	15.67	3.10	5.25	8.95	0.56	5.05
762.0- 765.0	1.58	13.64	3.11	4.72	8.63	0.51	4.39
795.5- 798.6	1.80	12.59	4.14	4.95	6.99	0.43	3.04
823.0- 826.0	2.09	12.53	3.47	4.97	6.00	0.60	3.61
847.3- 850.4	1.90	10.14	3.01	4.23	5.34	0.63	3.37
883.9- 887.0	3.19	14.61	3.57	6.21	4.58	0.89	4.09
914.4- 917.4	1.94	10.15	2.72	4.18	5.23	0.71	3.73
938.8- 941.8	1.79	11.56	3.19	4.48	6.46	0.56	3.62
975.4- 978.4	2.37	13.74	3.91	5.53	5.80	0.61	3.51
984.5- 987.6	2.05	14.99	3.58	5.46	7.31	0.57	4.19
993.6- 996.7	2.19	14.11	2.85	5.19	6.44	0.77	4.95
1005.8-1008.9	3.44	16.42	3.37	6.71	4.77	1.02	4.87
1015.0-1018.0	2.19	14.46	3.58	5.46	6.60	0.61	4.04
1033.3-1036.3	1.97	6.71	4.35	3.95	3.41	0.45	1.54
1048.5-1051.6	2.55	10.31	3.48	4.86	4.04	0.73	2.96
1063.8-1066.8	2.81	11.96	3.23	5.32	4.26	0.87	3.70
1094.2-1097.3	2.40	11.54	3.00	4.87	4.81	0.80	3.85
1130.8-1133.9	2.65	17.36	3.18	6.27	6.55	0.83	5.46
1155.2-1158.2	2.79	20.26	3.35	6.99	7.26	0.83	6.05
1164.3-1167.4	1.51	12.38	3.43	4.50	8.20	0.44	3.61
1170.4-1173.5	1.84	14.16	3.51	5.12	7.70	0.52	4.03
1182.6-1185.7	2.34	18.51	3.44	6.34	7.91	0.68	5.38
1191.8-1194.8	3.30	14.93	3.14	6.24	4.52	1.05	4.75
1213.1-1216.2	2.82	16.03	3.38	6.18	5.68	0.83	4.74
1225.3-1228.3	1.93	8.56	2.10	3.69	4.44	0.92	4.08
1240.5-1243.6	2.27	9.92	2.67	4.36	4.37	0.85	3.72
1249.7-1252.7	2.66	14.30	3.10	5.64	5.38	0.86	4.61
1283.2-1286.3	2.42	11.12	2.85	4.76	4.60	0.85	3.90
1313.7-1316.7	2.01	14.75	2.85	5.19	7.34	0.71	5.18
1325.9-1328.9	2.82	12.83	3.07	5.45	4.55	0.92	4.18
1338.1-1341.1	4.06	20.74	3.50	8.06	5.11	1.16	5.93
1344.2-1347.2	3.68	27.49	3.86	9.23	7.47	0.95	7.12
1353.3-1356.4	3.15	25.37	3.96	8.44	8.05	0.80	6.41
1356.4-1359.4	3.01	20.29	3.68	7.25	6.74	0.82	5.51
1368.6-1371.6	3.15	12.20	3.35	5.64	3.87	0.94	3.64
1380.7-1383.8	1.66	11.90	2.70	4.32	7.17	0.61	4.41
1402.1-1405.1	2.07	12.57	2.91	4.81	6.07	0.71	4.32
1432.6-1435.6	1.61	12.19	2.82	4.37	7.57	0.57	4.32
1463.0-1466.1	2.37	11.91	2.28	4.73	5.03	1.04	5.22
1499.6-1502.7	2.77	10.26	2.49	4.75	3.70	1.11	4.12
1527.0-1530.1	1.92	9.75	2.88	4.13	5.08	0.67	3.39
1557.5-1560.6	2.16	14.67	2.67	5.23	6.79	0.81	5.49
1566.7-1569.7	3.43	12.20	2.65	5.66	3.56	1.29	4.60
1572.8-1575.8	1.88	16.51	2.51	5.35	8.78	0.75	6.58
1581.9-1585.0	4.09	44.90	2.56	12.66	10.98	1.60	17.54
1588.0-1591.1	2.75	30.91	2.60	8.89	11.24	1.06	11.89
1597.2-1600.2	1.76	18.73	3.29	5.92	10.64	0.53	5.69
1615.4-1618.5	1.90	12.89	2.60	4.67	6.78	0.73	4.96
1645.9-1649.0	1.64	16.13	3.15	5.27	9.84	0.52	5.12
1682.5-1685.5	1.46	17.15	2.92	5.28	11.75	0.50	5.87
1703.8-1706.9	1.87	15.08	2.46	5.05	8.06	0.76	6.13
1713.0-1716.0	1.62	11.82	2.65	4.26	7.30	0.61	4.46
1743.5-1746.5	2.74	23.65	2.55	7.42	8.63	1.07	9.27
1764.8-1767.8	1.85	13.56	2.90	4.85	7.33	0.64	4.68
1801.4-1804.4	1.98	13.52	2.70	4.88	6.83	0.73	5.01
1831.8-1834.9	2.44	12.69	2.62	5.03	5.20	0.93	4.84

TABLE 2.—*Summary of radioelement and radiogenic heat analyses on 229 core samples from a drill hole in Wind River Mountains, Wyoming—Continued*

Sample depth (meters)	RaeU (ppm)	Th (ppm)	K (percent)	Heat (µcal/g-yr)	Th/RaeU	RaeU/Kx10⁻⁴	Th/Kx10⁻⁴
1859.3-1862.3	1.47	12.58	2.91	4.37	8.56	0.51	4.32
1868.4-1871.5	1.40	12.99	3.05	4.44	9.28	0.46	4.26
1874.5-1877.6	1.60	17.12	2.60	5.29	10.70	0.62	6.58
1883.7-1886.7	1.80	13.75	2.43	4.72	7.64	0.74	5.66
1889.8-1892.8	2.11	14.25	2.43	5.05	6.75	0.87	5.86
1895.9-1898.9	1.38	9.23	2.70	3.58	6.69	0.51	3.42
1902.0-1905.0	0.77	4.57	2.51	2.15	5.94	0.31	1.82
1914.1-1917.2	1.51	8.57	2.34	3.45	5.68	0.65	3.66
1923.3-1926.3	1.05	11.67	2.30	3.72	11.11	0.46	5.07
1932.4-1935.5	1.68	22.02	2.11	6.20	13.11	0.80	10.44
1941.6-1944.6	1.20	15.98	2.07	4.63	13.32	0.58	7.72
1947.7-1950.7	1.33	20.35	1.87	5.55	15.30	0.71	10.88
1950.7-1953.8	0.91	12.08	1.82	3.57	13.27	0.50	6.64
1959.9-1962.9	1.06	35.42	2.92	8.65	33.42	0.36	12.13
1969.0-1972.1	2.21	38.03	2.87	9.99	17.21	0.77	13.25
1978.2-1981.2	1.83	21.12	2.90	6.34	11.54	0.63	7.28
1984.2-1987.3	1.39	16.64	2.71	5.07	11.97	0.51	6.14
1993.4-1994.9	1.81	21.89	2.58	6.40	12.09	0.70	8.48
2002.5-2004.1	2.08	25.65	2.47	7.32	12.33	0.84	10.38
2011.7-2013.2	1.22	10.34	2.17	3.54	8.48	0.56	4.76
2020.8-2022.3	1.36	15.71	2.47	4.80	11.55	0.55	6.36
2026.9-2030.0	1.31	12.12	2.74	4.12	9.25	0.48	4.42
2037.6-2039.1	1.23	13.78	3.23	4.53	11.20	0.38	4.27
2045.2-2046.7	1.15	15.85	3.22	4.88	13.78	0.36	4.92
2062.0-2063.5	1.27	16.92	3.16	5.16	13.32	0.40	5.35
2072.6-2075.7	1.20	17.84	3.30	5.33	14.87	0.36	5.41
2094.0-2097.0	1.01	12.50	3.29	4.13	12.38	0.31	3.80
2106.2-2107.7	1.16	21.23	3.26	5.97	18.30	0.36	6.51
2110.7-2112.3	1.13	17.47	3.30	5.21	15.46	0.34	5.29
2121.4-2124.5	1.05	19.61	3.10	5.53	18.68	0.34	6.33
2130.6-2133.6	1.56	18.31	3.20	5.66	11.74	0.49	5.72
2139.7-2142.7	1.15	18.49	3.41	5.46	16.08	0.34	5.42
2148.8-2151.9	1.06	13.24	3.53	4.37	12.49	0.30	3.75
2158.0-2161.0	2.88	30.30	3.44	9.09	10.52	0.84	8.81
2167.1-2170.2	1.62	20.49	3.09	6.11	12.65	0.52	6.63
2176.3-2179.3	1.07	14.11	3.06	4.43	13.19	0.35	4.61
2188.5-2191.5	1.28	15.76	2.98	4.89	12.31	0.43	5.29
2200.7-2203.7	1.03	16.44	3.39	4.96	15.96	0.30	4.85
2206.8-2209.8	0.83	11.79	1.58	3.39	14.20	0.53	7.46
2218.9-2222.0	0.88	15.67	3.23	4.65	17.81	0.27	4.85
2225.0-2228.1	0.91	12.91	3.28	4.13	14.19	0.28	3.94
2237.2-2240.3	1.06	14.74	3.46	4.66	13.91	0.31	4.26
2249.4-2252.5	1.05	15.16	3.52	4.75	14.44	0.30	4.31
2258.6-2261.6	1.20	15.08	3.43	4.82	12.57	0.35	4.40
2267.7-2270.8	0.99	14.64	3.38	4.56	14.79	0.29	4.33
2279.9-2283.0	0.99	15.75	3.48	4.81	15.91	0.28	4.53
2289.0-2292.1	1.09	14.22	3.12	4.48	13.05	0.35	4.56
2319.5-2322.6	1.05	19.93	3.43	5.68	18.98	0.31	5.81
2350.0-2353.1	1.11	16.52	3.51	5.06	14.88	0.32	4.71
2383.5-2385.1	1.16	17.18	2.65	5.00	14.81	0.44	6.48
2411.0-2414.0	0.93	14.35	3.25	4.43	15.43	0.29	4.42
2435.4-2438.4	1.10	13.65	3.37	4.44	12.41	0.33	4.05
2441.4-2444.5	0.84	11.75	3.38	3.88	13.99	0.25	3.48
2465.8-2468.9	1.00	11.62	3.54	4.01	11.62	0.28	3.28
2505.5-2508.5	1.07	15.55	3.36	4.80	14.53	0.32	4.63
2535.9-2539.0	1.10	15.76	3.20	4.82	14.33	0.34	4.93
2560.3-2563.4	1.11	15.55	3.30	4.81	14.01	0.34	4.71
2584.7-2587.8	1.09	14.14	3.00	4.43	12.97	0.36	4.71
2593.8-2596.9	1.19	15.13	3.38	4.81	12.71	0.35	4.48
2621.3-2624.3	1.06	14.76	3.38	4.64	13.92	0.31	4.37
2654.8-2657.9	1.18	17.76	1.35	4.78	15.05	0.87	13.16
2664.0-2667.0	1.81	26.43	2.53	7.29	14.60	0.72	10.45
2673.1-2676.1	1.71	26.33	2.41	7.16	15.40	0.71	10.93
2682.2-2685.3	1.62	26.55	2.85	7.26	16.39	0.57	9.32
2694.4-2697.5	2.04	27.75	2.97	7.84	13.60	0.69	9.34

TABLE 2.—*Summary of radioelement and radiogenic heat analyses on 229 core samples from a drill hole in Wind River Mountains, Wyoming—Continued*

Sample depth (meters)	RaeU (ppm)	Th (ppm)	K (percent)	Heat (µcal/g-yr)	Th/RaeU	RaeU/Kx10⁻⁴	Th/Kx10⁻⁴
2700.5-2703.6	2.45	27.96	2.72	8.11	11.41	0.90	10.28
2715.8-2718.8	2.41	25.82	2.72	7.66	10.71	0.89	9.49
2724.9-2728.0	2.14	28.33	2.76	7.97	13.24	0.78	10.26
2734.1-2737.1	2.30	20.48	2.36	6.41	8.90	0.97	8.68
2746.2-2749.3	1.64	18.53	2.64	5.62	11.30	0.62	7.02
2767.6-2770.6	1.99	24.57	2.67	7.09	12.35	0.75	9.20
2776.7-2779.8	1.87	23.24	2.68	6.74	12.43	0.70	8.67
2788.9-2792.0	2.37	18.78	2.69	6.21	7.92	0.88	6.98
2798.1-2801.1	2.91	17.17	2.86	6.33	5.90	1.02	6.00
2807.2-2810.3	1.58	8.14	3.11	3.62	5.15	0.51	2.62
2816.4-2819.4	2.33	12.79	2.78	5.01	5.49	0.84	4.60
2828.5-2831.6	1.12	7.87	2.81	3.15	7.03	0.40	2.80
2840.7-2843.8	1.18	8.02	3.09	3.30	6.80	0.38	2.60
2846.8-2849.9	1.22	9.60	3.05	3.63	7.87	0.40	3.15
2862.1-2865.1	0.91	6.48	3.04	2.78	7.12	0.30	2.13
2874.3-2877.3	1.19	13.13	2.87	4.27	11.03	0.41	4.57
2886.5-2889.5	1.15	16.06	3.06	4.88	13.97	0.38	5.25
2898.6-2901.7	1.22	16.16	3.05	4.95	13.25	0.40	5.30
2907.8-2910.8	13.86	23.05	3.74	15.74	1.66	3.71	6.16
2920.0-2923.0	6.16	21.71	3.21	9.71	3.52	1.92	6.76
2932.2-2935.2	2.50	22.21	2.96	7.07	8.88	0.84	7.50
2941.3-2944.4	1.90	21.40	3.06	6.49	11.26	0.62	6.99
2950.5-2953.5	1.72	16.76	2.88	5.39	9.74	0.60	5.82
2962.7-2965.7	2.08	18.22	2.86	5.93	8.76	0.73	6.37
2974.8-2977.9	1.71	15.54	2.63	5.07	9.09	0.65	5.91
2984.0-2987.0	2.31	13.90	2.43	5.12	6.02	0.95	5.72
2993.1-2996.2	1.87	14.14	2.86	4.97	7.56	0.65	4.94
3002.3-3005.3	1.56	18.48	2.83	5.60	11.85	0.55	6.53
3014.5-3017.5	1.52	17.77	2.87	5.44	11.69	0.53	6.19
3023.6-3026.7	2.56	23.03	2.54	7.16	9.00	1.01	9.07
3035.8-3038.9	2.16	13.02	2.46	4.84	6.03	0.88	5.29
3045.0-3048.0	1.73	10.52	2.42	4.02	6.08	0.71	4.35
3051.0-3054.1	1.71	9.89	2.65	3.94	5.78	0.65	3.73
3060.2-3063.2	2.66	16.89	2.57	6.01	6.35	1.04	6.57

The thorium content for all samples ranges from 4.57 to 78.3 ppm; the mean and standard deviation is 17.6±8.76 ppm, which is very near the average for silicic igneous rocks (table 3). Most of the thorium analyses are within the range of averages reported for intermediate and silicic igneous rocks. The thorium content in the depth interval from 2,040 to 2,650 m is limited to a narrower range than that of all samples, but the mean content (16.1±3.38 ppm) is not significantly different. Virtually all the samples in which the thorium content is greater than three standard deviations from the mean are from a highly fractured zone near the top of the drill hole.

The potassium content ranges from 1.35 to 5.23 percent; the mean and standard deviation is 3.09±0.58 percent. The potassium content in most of the samples is within the range commonly measured in rock types ranging from granodiorite to quartz monzonite. The mean and standard deviation of the potassium analyses in the interval from 2,040 to 2,650 m is 3.24±0.34 percent.

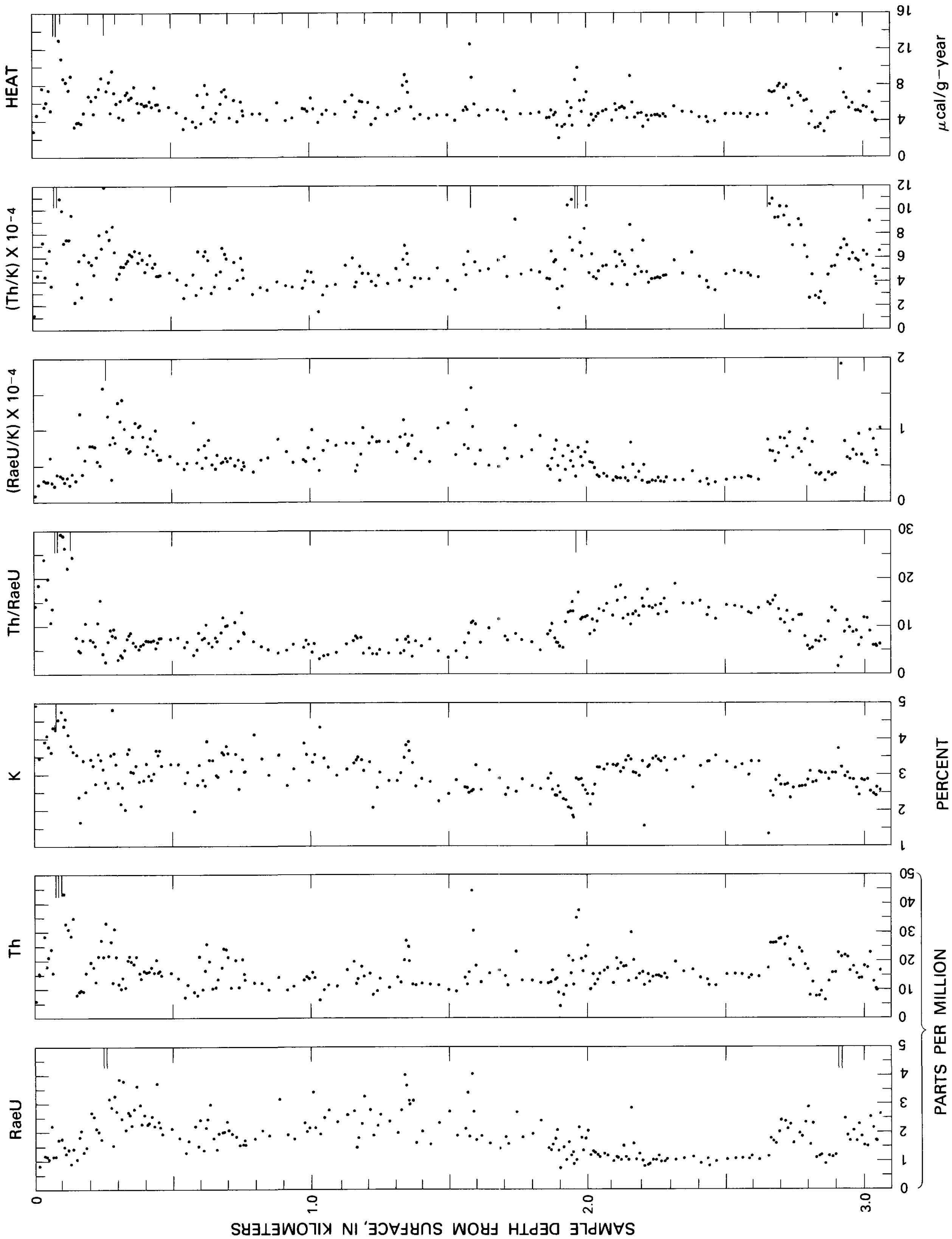


FIGURE 5.—Radioelement concentrations and ratios and radiogenic heat in 3.06-m-deep drill hole. Long tick marks indicate points beyond scale limit. Sample depths are at midpoint of sampled interval.

TABLE 3.—*Averages of radioelement contents and ratios and radiogenic heat for samples from a 3.06-kilometer drill hole, Wind River Mountains, Wyoming, and summary of published averages for igneous rocks*

[Drill hole data reported as average ±1 standard deviation]

Constituent	All samples		2040- to 2650-m interval		Average in igneous rocks			
	Average	Range	Average	Range	Continental crust	Mafic	Intermediate	Silicic
RaeU (ppm)	2.02±1.33	0.42-13.86	1.15±0.33	0.83- 2.88	[a] [b]2.8	[e]0.9	[e]2.0-2.6	[e]4 [e]4.7 [e]4.75
Th (ppm)	17.6 ±8.8	4.57-78.3	16.1 ±3.4	11.6 -30.3	[c]6-10	[e]2.7	[e]8.5-9.3	[a]20 [a]18
K (percent)	3.09±0.58	1.35- 5.23	3.24±0.34	1.58- 3.54	[d]1.6-2.6 [b]2.6	[d]0.6-0.75	[d]2.7-3.0	[a]3.6 [b]3.79
Th/RaeU	10.3 ±6.7	1.66-67.5	14.3 ±2.0	10.5 -19.0	[d]3.5-4 [b]3.6	[c]≤3 [b]4.8	[f]4.1	[f]4.5 [e]4.0
RaeU/K×10^{-4}	0.68±0.44	0.09- 4.64	0.36±0.10	0.25- 0.84	[a]1	[b]0.6	[g]0.7-1	[b]1.29
Th/K×10^{-4}	5.76±2.43	1.20-15.9	5.01±1.12	3.28- 8.81	[c]3.3	[b]2.8	[g]2.8-3.4	[e]5.0 [b]4.9
Heat (μcal/g-yr)	5.84±2.20	1.93-17.9	4.93±0.90	3.39- 9.09	[g]3.7-4.6	[g]1.4	[g]3.9-4.6	[g]7.5-8.5

[a]Rogers and Adams (1969b).
[b]Heier and Rogers (1963).
[c]Rogers and Adams (1969a).
[d]Cocco and others (1970).
[e]Clark, Peterman, and Heier (1966).
[f]Z. E. Peterman (written commun., 1963).
[g]Calculated from published values.

The uranium (RaeU) content of all samples from the exploratory hole ranges from 0.42 to 13.86 ppm. Most of the uranium analyses are within the range of averages for mafic to intermediate rocks. The mean and standard deviation is 2.02±1.33 ppm, which is near the average for diorite and quartz diorite (Clark and others, 1966). The mean and standard deviation of the uranium content for the depth interval from 2,040 to 2,650 m is 1.15±0.33 ppm, which is close to the average for mafic igneous rocks (table 3). The uranium content in this 610-m interval is less than the content usually measured in quartz monzonite. A histogram of the data (fig. 6) shows that low uranium content is not unique to this interval, but most of the samples have higher content.

The Th/RaeU ratio ranges from 1.66 to 67.5. A histogram of the data (fig. 6) indicates a bimodal distribution with the two groups separated at a ratio of about 10.0. The data from the 2,040- to 2,650-m depth interval are limited to and contribute greatly to the group of higher ratios. The average Th/U ratio in most rocks ranges from 3 to 5; virtually all samples from the drill hole have ratios greater than normal. These abnormally high ratios are indicative of either uranium depletion or excess thorium.

Average U/K×10^{-4} ratios range from 0.6 in mafic rocks to 1.3 in silicic igneous rocks. The mean and standard deviation for all samples from the exploratory hole is 0.68±0.44, and for the 2,040- to 2,650-m depth interval they are 0.36±0.10. The ratios from the drill hole samples indicate either that the rock types are in the mafic to intermediate classification, that uranium is depleted, or that potassium is in excess.

Average Th/K×10^{-4} ratios range from 2.8 in mafic rocks to 5.0 in silicic igneous rocks. Mean and standard deviations for the drill hole data are 5.76+± 2.43 for all samples, and 5.01±1.12 for the 2,040- to 2,650-m depth interval; a histogram of the data indicates no significant difference in the two sets of data. The means are not greatly different from the average for silicic igneous rocks, although the ratios in the small percentage of the samples that contain anomalously large amounts of thorium are significantly greater than normal.

A histogram of the radiogenic heat data (fig. 6) indicates no major difference between the distribution for all samples and that for the 2,040- to 2,650-m depth interval. The means and standard deviations for these two groups of samples are 5.84±2.20 and 4.93±0.90, respectively. Most of the radiogenic heat values are similar to those calculated in intermediate to silicic igneous rocks.

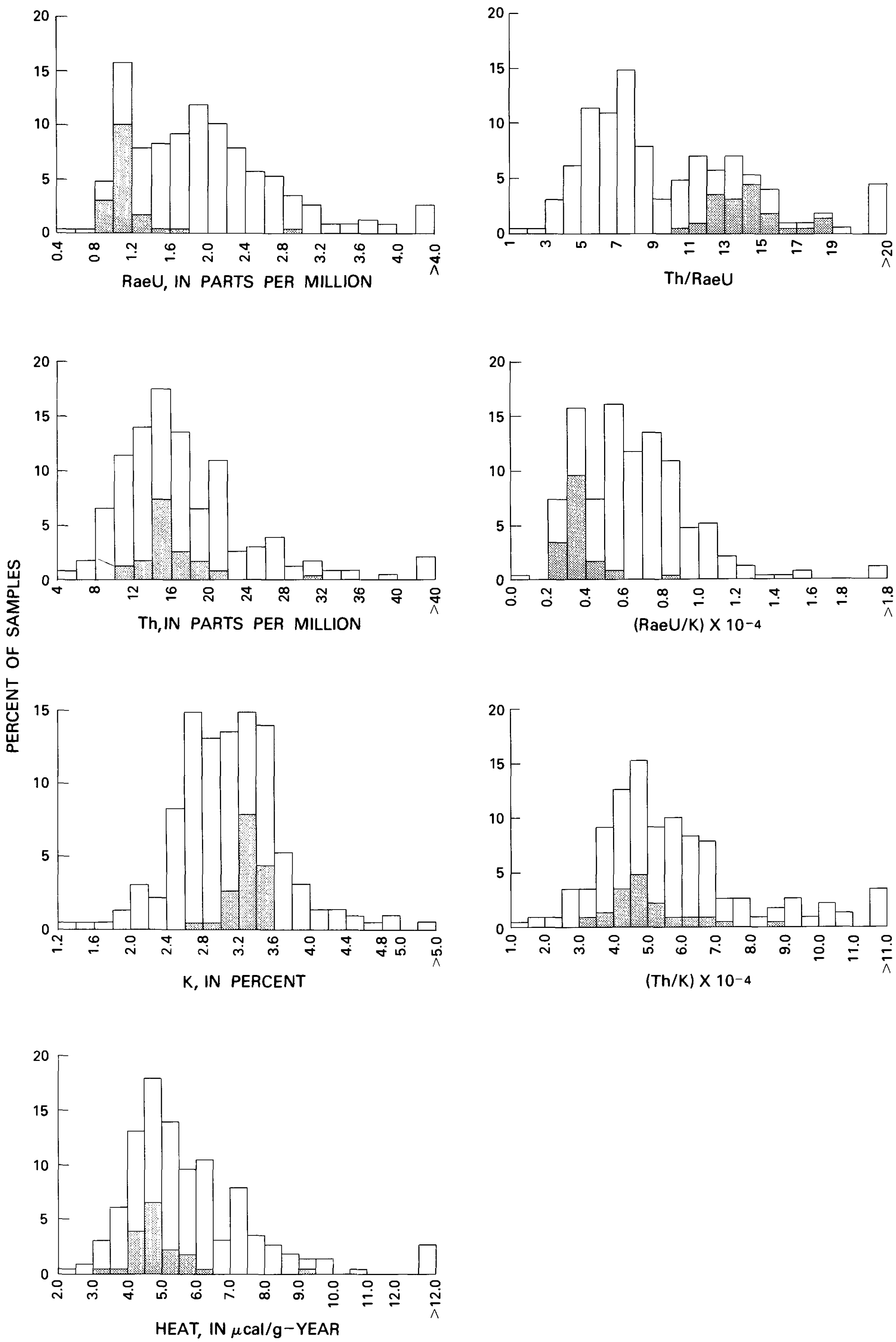


FIGURE 6.—Frequency distribution of radioelement concentrations and ratios and radiogenic heat. Open bars are all 229 samples; shaded bars are 37 samples at depth interval 2,040–2,650 m plotted as a percent of the total.

CONCLUSIONS

The variable distributions of the uranium, thorium, and potassium contents throughout the depth of the drill hole substantiate observations of similar variations in rock type and composition determined from petrographic examinations of a few core samples from the hole. The radioelement data and geophysical logs of the hole indicate that the drill hole penetrates a thick section of layered, fractured, heterogeneous rock.

Thorium and potassium analyses indicate that the rock types range from intermediate to silicic and that virtually all the samples are more silicic than granodiorite, based on published average radioelement contents for those rock classifications.

Radium equivalent uranium analyses indicate that the uranium content in most of the samples is less than the average reported for granodiorite. The amount of uranium measured may be less than the amount present because of a deficiency of daughter products in the uranium decay series. If the uranium is not in equilibrium, the disequilibrium is probably long lived and probably occurs among the isotopes ^{238}U, ^{234}U, and ^{230}Th. If the uranium series is in equilibrium, abnormally low uranium content in the original material from which the rock was formed is indicated. We favor the possibility that the uranium was mobilized and removed, probably at the time of metamorphism.

Uranium content is lower in relatively unfractured sections, for example, in the depth interval from 2,040 to 2,650 m, than it is in highly fractured sections of the hole. The uranium content in the unfractured sections may represent the content of that rock type prior to the occurrence of the overthrust and its associated fracturing; if so, the higher uranium content in the fractured zones may represent enrichment through migration of uranium from other areas in the Wind River Mountains. If the uranium loss in the unfractured rock occurred during or after the thrusting, the uranium may have migrated vertically and redeposited in the fractures.

REFERENCES CITED

Clark, S. P., Jr., Peterman, Z. E., and Heier, K. S., 1966, Abundances of uranium, thorium, and potassium, sec. 24 *of* Handbook of physical constants (revised ed.): Geological Society of America Memoir 97, p. 521–541.

Cocco, G., Fanfani, L., Zanazzi, P. F., Heier, K. S., and Billings, G. K., 1970, Potassium, chapter 19 *of* Wedepohl, K. H., ed., Handbook of geochemistry, v. 2, no. 2: New York, Springer-Verlag, p. A1–N1.

Ebens, R. J., and Smithson, S. B., 1966, Petrography of Precambrian rocks from a 3.05-kilometer-deep borehole, Wind River Mountains, Wyoming: University of Wyoming Contributions to Geology, v. 5, p. 31–38.

Heier, K. S., and Rogers, J. J. W., 1963, Radiometric determination of thorium, uranium, and potassium in basalts and in two magmatic differentiation series: Geochimica et Cosmochimica Acta, v. 27, no. 2, p. 137–154.

Lachenbruch, A. H., and Bunker, C. M., 1971, Vertical gradients of heat production in the continental crust, 2. Some estimates from borehole data: Journal of Geophysical Research, v. 76, no. 17, p. 3852–3860.

Rogers, J. J. W., and Adams, J. A. S., 1969a, Thorium, chapter 90 *of* Wedepohl, K. H., ed., Handbook of geochemistry, v. 2, no. 4: New York, Springer-Verlag, p. B1–O1.

——1969b, Uranium, chapter 92 *of* Wedepohl, K. H., ed., Handbook of geochemistry, v. 2, no. 4: New York, Springer-Verlag, p. B1–O1.

Schonfeld, Ernest, 1966, Alpha M—An improved computer program for determining radioisotopes by least-squares resolution of the gamma-ray spectra: Oak Ridge, Tenn., U.S. National Laboratory (Publications), ORNL–3975, 43 p.

Smithson, S. B., and Ebens, R. J., 1971, Interpretation of data from a 3.05-kilometer borehole in Precambrian crystalline rocks, Wind River mountains, Wyoming: Journal of Geophysical Research, v. 76, p. 7079–7087.

Ages of Igneous Rocks in the South Park–Breckenridge Region, Colorado, and their Relation to the Tectonic History of the Front Range Uplift

By BRUCE BRYANT, RICHARD F. MARVIN, CHARLES W. NAESER, *and* HARALD H. MEHNERT

SHORTER CONTRIBUTIONS TO ISOTOPE RESEARCH IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199-C

CONTENTS

ILLUSTRATIONS

TABLES

AGES OF IGNEOUS ROCKS IN THE SOUTH PARK—BRECKENRIDGE REGION, COLORADO, AND THEIR RELATION TO THE TECTONIC HISTORY OF THE FRONT RANGE UPLIFT

By BRUCE BRYANT, RICHARD F. MARVIN, CHARLES W. NAESER, and HARALD H. MEHNERT

ABSTRACT

Potassium-argon ages of biotite and fission-track ages of zircon, sphene, and apatite show that porphyries of the Colorado mineral belt between the Breckenridge and Tarryall districts are predominantly of late Eocene and early Oligocene age, ranging from 35 to 42 m.y. (million years) old. A discrepancy between biotite ages of 44 to 50 m.y. and zircon, sphene, and apatite ages of 35-42 m.y. in some rocks may be due to excess argon derived from Precambrian basement rocks rather than to later regional heating or slow cooling. Concordant ages of biotite and zircon were found in one sample of porphyry at 41 m.y. The existence of coeval extrusive rocks is indicated by a 40-m.y.-old andesite in a paleovalley fill in southwestern South Park.

Radiometric ages show that sedimentary and volcanic rocks were deposited in the South Park basin throughout the Paleocene. The main phase of the Laramide orogeny in South Park took place in the early Eocene, when the basin fill was folded, faulted, and overridden by the west margin of the Front Range uplift and before intrusion of the porphyries.

INTRODUCTION

The South Park-Breckenridge region lies at the intersection of the northeast-trending Colorado mineral belt and the north-northwest-trending western margin of the Front Range uplift (fig. 7). The Colorado mineral belt, characterized by many Late Cretaceous and Tertiary intrusive rocks and associated mineral deposits, was recognized by Spurr and Garrey (1908) and described in some detail by Lovering and Goddard (1950). Lovering and Goddard had no way of determining the ages of the intrusive rocks, but determined relative ages in part on the assumption that petrographically similar rocks were of similar age. They concluded that intrusion of the igneous rocks of the belt occurred over a long period of time and progressed from southwest to northeast.

More recently, isotopic dating has furnished ages of the intrusive porphyries of the mineral belt. K-Ar ages of minerals from the porphyries in the northeastern part of the belt and in the Leadville district adjacent to the Sawatch Range are 72 to 64 m.y., or Late Cretaceous to earliest Paleocene (Hart, 1960; 1964; Pearson and others, 1962). Further isotopic dating revealed that a few of the intrusives are 26 to 38 m.y. old (Oligocene), principally the ones associated with molybdenum deposits (McDowell, 1971; Taylor and others, 1968; Schassberger, 1972). Farther southwest along the mineral belt, isotopic dating of rocks in the Aspen region showed that small intrusives in the mining district are 67 to 72 m.y. old (Late Cretaceous) but that the larger igneous complexes of the Elk Mountains are 29 to 34 m.y. old (Oligocene) (Obradovich and others, 1969). This latter age range is similar to that of the bulk of the volcanic field of the San Juan Mountains in southwestern Colorado (Lipman and others, 1970). Relatively few ages in the range 45-55 m.y. have been obtained from intrusive rocks in the mineral belt, but some have been reported.

Intrusive rocks along a 20-km segment of the mineral belt in the South Park-Breckenridge region have been determined by us to be late Eocene to early Oligocene in age, 41 to 35 m.y. old. The relation of these rocks to the fault at the west margin of the Front Range uplift indicates that these intrusions occurred after Laramide uplift of the Front Range block.

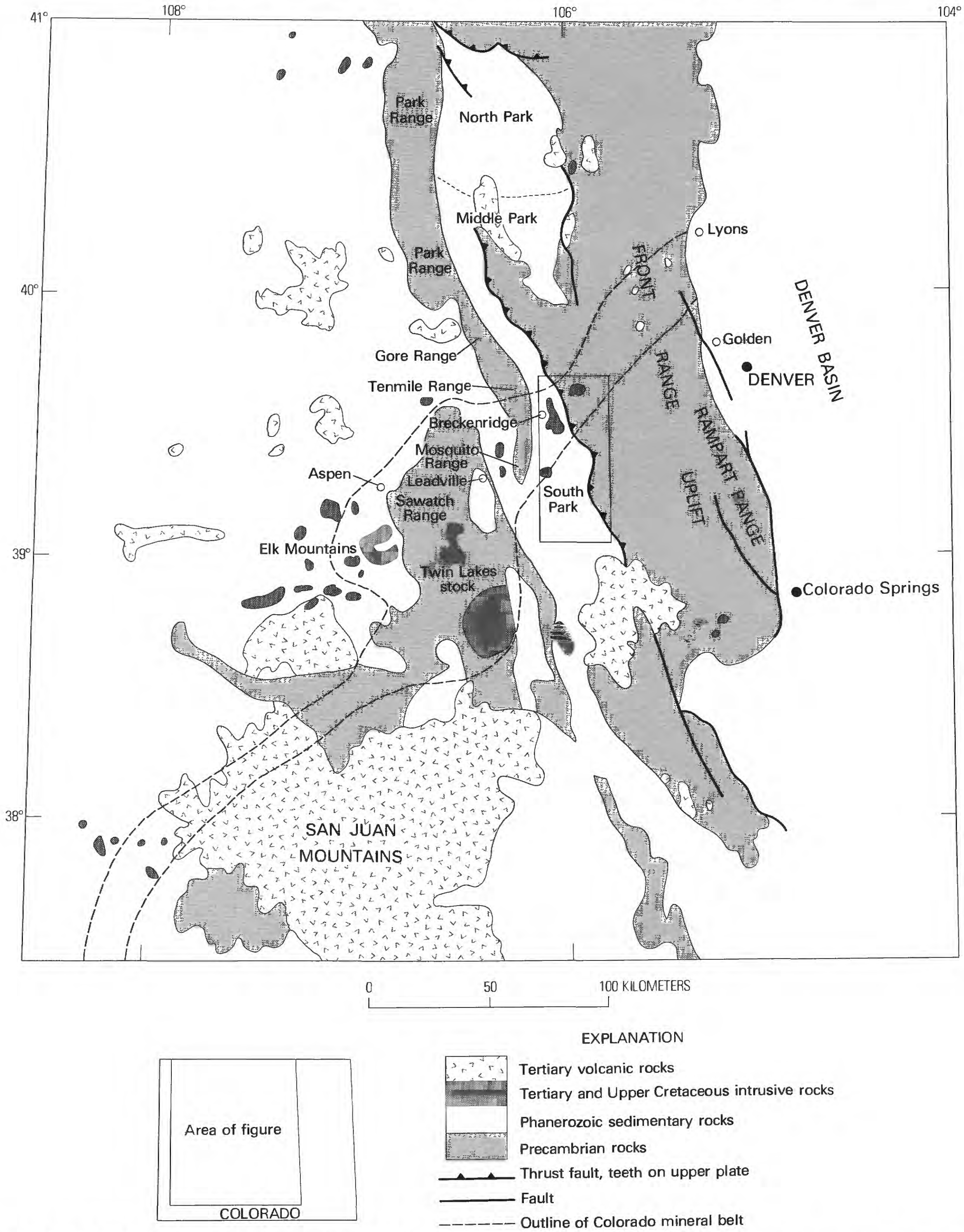


FIGURE 7.—Index map of central and western Colorado showing the location of the South Park-Breckenridge area outlined and major tectonic features associated with the Front Range uplift. Simplified from King and Beikman (1974).

OUTLINE OF THE GEOLOGY OF THE SOUTH PARK-BRECKENRIDGE REGION

A continuous downfolded and faulted belt of Cretaceous and older sedimentary rocks, 250 km long, borders the Front Range on the west and separates it from the Park, Gore, Tenmile, and Mosquito Ranges farther west (fig. 7). Mountains formed by Tertiary igneous rock divide this belt into three broad basins: North, Middle, and South Parks. Along 150 km of the west margin of the Front Range uplift, Precambrian rocks are thrust westward over sedimentary rocks of the basins along the Williams Range fault in Middle Park and the Elkhorn fault in South Park (fig. 8). In the South Park–Breckenridge region, Tertiary intrusives of the Colorado mineral belt interrupt the belt of sedimentary rock west of the Front Range uplift and separate Middle Park from South Park.

In South Park, Tertiary sedimentary and volcanic rocks as much as 3,000 m thick form the South Park Formation (Sawatzky, 1967; Wyant and Barker, 1976). The South Park Formation overlies the Upper Cretaceous Laramie Formation, Fox Hills Sandstone, and Pierre Shale. At the base of the South Park Formation are andesitic flows and breccias and tuffaceous sandstone and conglomerate of the Reinecker Ridge Volcanic Member (Wyant and Barker, 1976). These volcanic and volcaniclastic rocks are overlain by a conglomerate rich in igneous clasts in the basal part. Stratigraphically higher, the conglomerate also contains sedimentary clasts from Paleozoic and Mesozoic rocks that crop out on the west side of the South Park basin. Beds of sandstone, mudstone, and tuff interlayered with the conglomerate make up a large proportion of the upper part of the unit. The Link Spring Tuff Member, about 2,000 m above the base of the South Park Formation, consists of tuff, tuffaceous conglomerate, and andesite as much as 200 m thick. The upper part of the South Park Formation is composed of arkose, conglomerate, mudstone, and tuff and contains beds of boulder conglomerate in its highest part. Boulders in the conglomerate are as much as 3 m in diameter and are composed mainly of Precambrian granitic rock like that exposed along the margin of the Front Range uplift east of the Elkhorn fault. Although these rocks rest unconfromably on Cretaceous rocks, the principal deformation in the South Park basin occurred after deposition of the South Park Formation, because the main folds and faults deform both the Cretaceous and Tertiary rocks.

Volcanic rocks in the South Park Formation are thicker in the western part of South Park (fig. 8) and must have been derived from the area southwest of the intrusive rocks we have dated in this study, probably from near Leadville or east of Leadville, where igneous intrusive rocks of Paleocene age are exposed (Pearson and others, 1962; Young, 1972).

FISSION-TRACK DATING PROCEDURE

Sphene and zircon separates were dated by the external detection method, using muscovite as the detector. A geometry factor of 0.5 was used to determine the induced track density for the age equation. The apatite ages were determined using the population method. The defect density in most of the apatite concentrates was too high to permit the use of the external detection method. The neutron dose was determined by counting tracks in a muscovite detector, which covered National Bureau of Standards glass SRM 962 during its irradiation. This muscovite-glass pair has been calibrated using the NBS copper flux values. The errors on the apatite, sphene, and zircon (less than 4 grains) were calculated by combining the standard deviations (number of counts) for the induced and fossil counts. The standard deviations for samples in which five or more sphene or zircon grains were counted were calculated using the procedure outlined by Naeser and others (1978).

AGE OF THE SOUTH PARK FORMATION

The South Park Formation (Denver Formation of Stark and others, 1949) contains leaves indicative of a Paleocene age (Stark and others, 1949; Brown, 1962). The localities specified in these publications are all in the lower part of the South Park Formation, below the Link Springs Tuff Member. Sawatsky (1967) obtained a late Paleocene or early Eocene K/Ar whole-rock age of 56±2.6 m.y. from the lowest exposed flow in the Reinecker Ridge Volcanic Member at Devils Gap (fig. 8), the type locality of the Reinecker Ridge Volcanic Member (Wyant and Barker, 1976). That date suggested that much of the South Park Formation might be significantly younger than the comparable lower Tertiary deposits of the Denver Formation on the east side of the Front Range uplift.

Our studies of the South Park Formation, however, show that the epoch of sedimentation in the South Park basin was roughly comparable to that of the Denver Formation in the Denver basin, as earlier

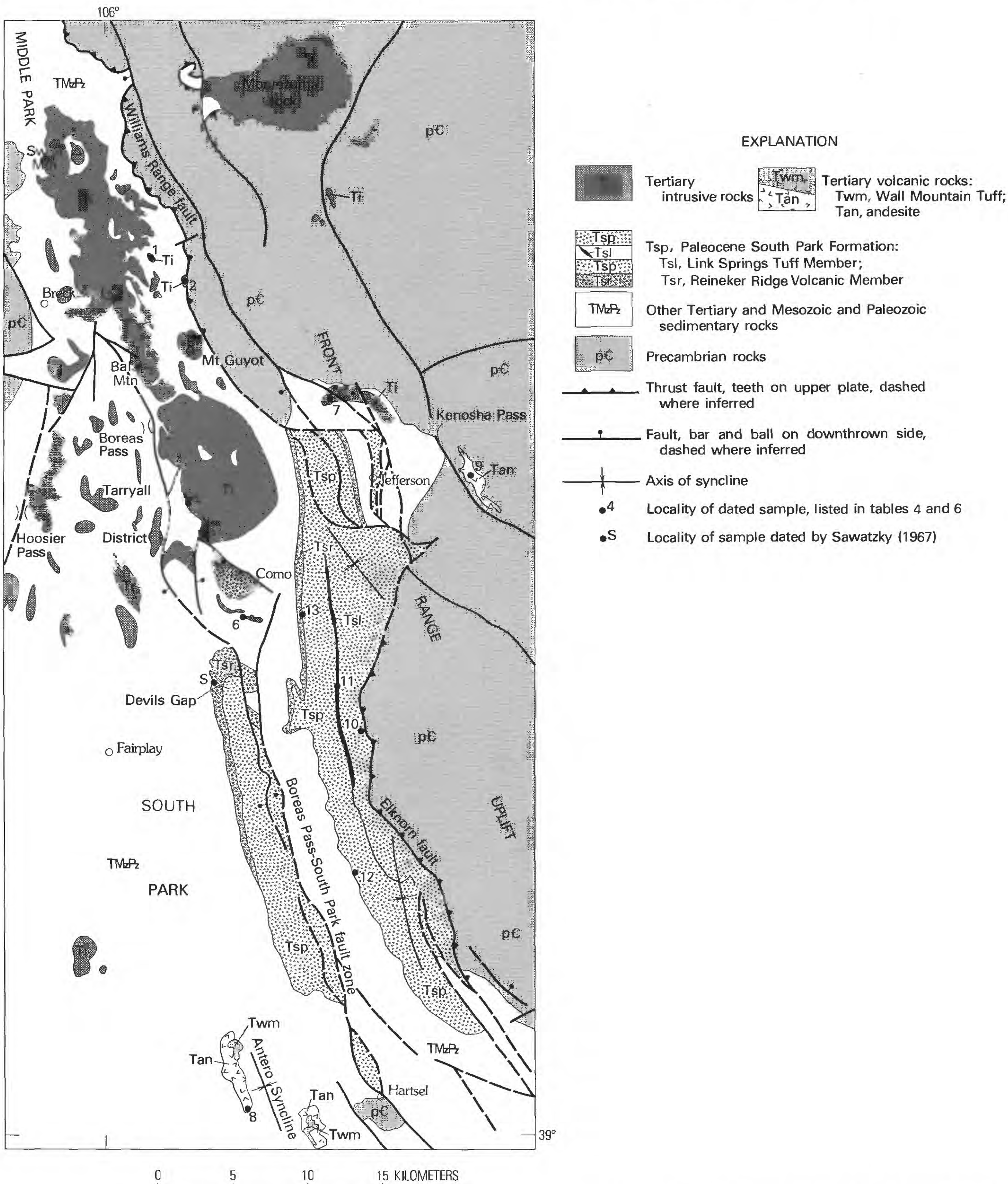


FIGURE 8.—Geologic map of the South Park-Breckenridge region showing location of samples from which minerals were dated (numbers indicate locality). Simplified from Bryant and others (1980); Tweto and others (1978), and Scott and others (1978).

workers believed. The age of samples from the base of the South Park Formation (localities 12 and 13, table 4 and fig. 8) is early Paleocene. The sample at locality 13 was taken about 200 m above the base of the Reinecker Ridge Volcanic Member and thus is from a horizon higher than that corresponding to Sawatzky's sample. According to Sawatzky's description of his dated sample and our observations at his sample locality, the rock there is altered. (See field no. 323, table 9.) Consequently, his whole-rock age may be too young. The sample from locality 12 is a crystal tuff from about 3 m above the base of the South Park Formation in an area where rocks younger than the Reinecker Ridge Volcanic Member form the base of the formation. The rock at this locality probably is stratigraphically equivalent to rocks directly above that member. The biotite ages from localities 12, 11, and 10 are progressively younger and fit the stratigraphy. Fission-track ages of coexisting zircons from these localities are in good agreement with the biotite ages—in great contrast to some of the biotite and zircon ages for the younger intrusives (fig. 9, table 4). These data show that deposition of the South Park Formation occupied the entire Paleocene. Some of the lowest beds may be of latest Cretaceous age, and the uppermost beds, which were not dated, might be as young as earliest Eocene.

INTRUSIVE ROCKS

In intrusive bodies of the Breckenridge area, Ransome (1911) and Lovering (1934) recognized three main rock types: a quartz monzonite porphyry distinguished by phenocrysts of potassic feldspar as much as several centimeters long; a monzonite porphyry characterized by smaller phenocrysts of hornblende, biotite, and plagioclase and by a lack of quartz phenocrysts; and an intermediate type they called quartz monzonite. Ransome (1911) found no contacts between the rock types and believed that they were closely related in age and origin. Lovering (1934) found a few exposures where the quartz monzonite porphyry cuts monzonite and quartz monzonite, and he inferred, assuming a normal sequence of magmatic differentiation, that the porphyritic quartz monzonite was younger than the other two rock types. In some intrusives, both Lovering and we have noted gradations between the monzonite and quartz monzonite. The mapping of those two rock types may be rather arbitrary in many places.

Pride and Robinson (1978) determined a sequence of intrusion in the area of the Wirepatch Mine, in the

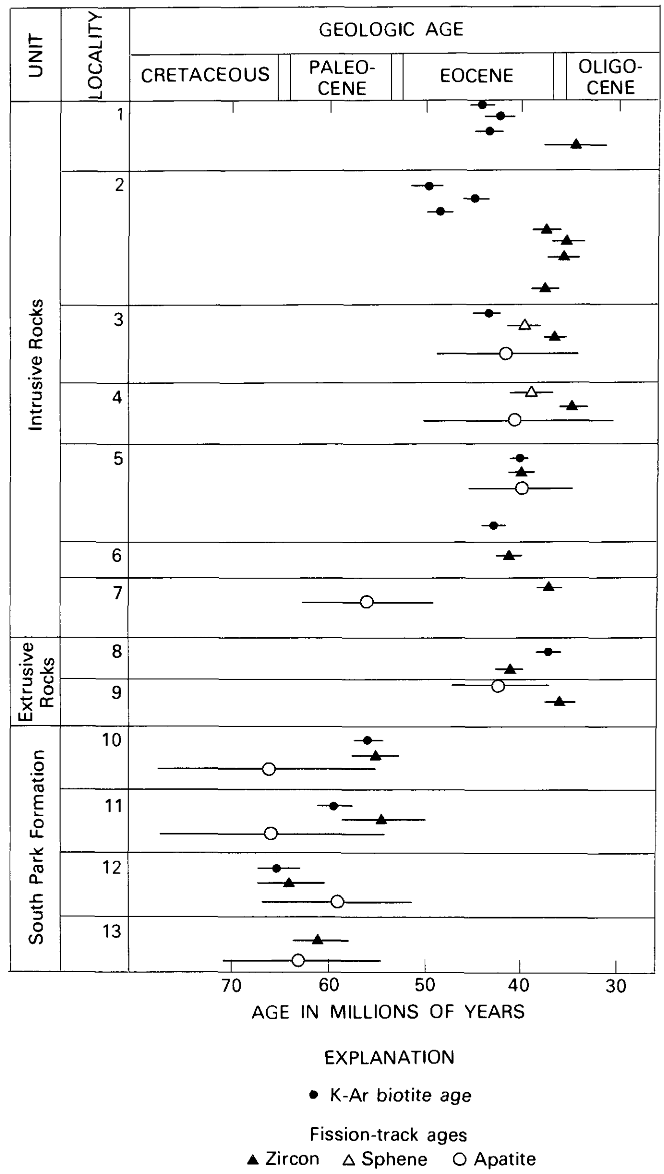


FIGURE 9.—Graphical representation of mineral ages from rocks in the South Park-Breckenridge region. Horizontal bars show range of uncertainty (2 sigma) for each determination. Two lines between epochs delineate range of uncertainity of absolute age of boundary (J. D. Obradovich and G.A. Izett, written commun., 1979).

eastern part of the Breckenridge district, in which quartz monzonite porphyry is younger than monzonite poyphyry and also includes a younger rhyodacite porphyry and intrusive breccia. They cite an age of 41.4 m.y. for the rhyodacite porphyry but do not say how that age was determined.

In the Tarryall district, south of Breckenridge, Muilenburg (1925) mapped the south end of a large sill (the Bald Mountain sill, fig. 8) as quartz monzonite porphyry, because quartz phenocrysts were

TABLE 4.—*K-Ar and fission-track ages of igneous rocks in the South Park-Breckenridge region*

[Localities and sample descriptions in table 6; analytical data in tables 7 and 8 in appendix. Leaders (......) indicate no determination made.]

Loc. No.	Field No.	K-Ar biotite age	Fission-track age	Mineral dated
		Intrusive rocks		
1	223	44.8±1.5	35.1± 3.6	Zircon.
		43.1±1.0		
		[1] 44.0±1.0		
2	222	50.6±1.7	38.3± 1.8	Do.
		45.5±1.1	36.6± 2.0	Do.
		[2] 49.1±1.2	36.2± 1.6	Do.
	466	--------	38.2± 1.8	Do.
3	74	44.0±1.5	40.4± 1.7	Sphene.
			37.9± 1.6	Zircon.
			42.7± 8.2	Apatite.
4	233	--------	39.9± 2.0	Sphene.
			35.5± 1.4	Zircon.
			41.1±10	Apatite.
5	503	[3] 40.7±1.4	40.3± 1.8	Zircon.
			40.6± 5.8	Apatite.
	503a	43.2±1.5	---------	-------
6	502	--------	41.5± 1.8	Zircon.
7	328	--------	37.6± 1.5	Do.
			[4] 56.4± 7.4	Apatite.
		Extrusive rocks		
8	430a	37.8±0.9	41.5± 1.8	Zircon.
			42.8± 5.1	Apatite.
9	420	--------	36.4± 1.9	Zircon.
		South Park Formation		
10	W-1-75	56.3±1.3	55.5± 2.7	Zircon.
			66.5±11.6	Apatite.
11	150	59.7±2.0	54.7± 4.8	Zircon.
			66.4±12	Apatite.
12	444	65.5±1.6	64.1± 3.7	Zircon.
			59.3± 8.1	Apatite.
13	325	--------	60.9± 3.2	Zircon.
			63.3± 8.5	Apatite.

[1] Contains minor hornblende.
[2] Contains some hornblende.
[3] Contains minor hornblende and chlorite.
[4] Has many defects; age only approximate.

visible in the rock there. The north end of this sill was called monzonite porphyry by Ransome (1911). Muilenburg called an intermediate rock, containing less quartz, Silverheels Quartz Monzonite Porphyry, although he pointed out that it was impossible to consistently differentiate the two rock types. A third, more mafic rock type, he designated diorite porphyry. In the same region, Singewald (1942; 1951) mapped a monzonite porphyry containing little or no visible quartz, a quartz monzonite porphyry, and Lincoln Porphyry, characterized by large phenocrysts of potassic feldspar and resembling the quartz monzonite porphyry of Ransome (1911) in the Breckenridge district. Singewald (1942) also pointed out the difficulty of distinguishing between the first two map units. On his maps he designated the rock in the sill on Bald Mountain southwest of Breckenridge as quartz monzonite and diorite (1942) and as monzonite porphyry (1951).

Stark and others (1949) gave a formal name, Esche Porphyry, to the igneous rocks, including the south end of the Bald Mountain sill, on the northwest side of South Park near Como, and they described the Esche Porphyry as quartz monzonite porphyry and quartz diorite porphyry. They thought that the igneous rocks were emplaced contemporaneously with deposition of the South Park Formation, although they added that "at least some intrusions are later than the large north-trending faults of South Park."

This review of the rock names applied to the intrusive rocks of the South Park-Breckenridge region illustrates the lack of precision of field and petrographic determinations of the rock types. Chemical analyses (table 9; Ransome 1911; Muilenburg, 1925; Phair and Jenkins, 1975) show that these rocks range from rather potassic diorite to quartz monzonite (fig. 10). Most of the rocks are granodiorite to quartz monzonite, even though the term monzonite has been applied to some of the larger bodies, such as the Bald Mountain sill (localities 4 and 5, fig. 8).

Bryant and others (1980) generally followed the classification of Ransome (1911), because it seemed the most practical for purposes of field mapping (table 5).

The intrusive rocks occur as sills, plugs, and dikes, and they form the high peaks separating Middle Park from South Park. For example, Mt. Guyot (4,075 m) is a plug of the quartz monzonite (fig. 8, locality 3). Heat from this intrusion has metamorphosed Pierre Shale and a slice of Dakota Sandstone in the hanging wall of the Williams Range fault (fig. 8). Bald Mountain (4,170 m) is a sill of monzonite porphyry as much as 1 km thick; this sill cuts branches of the

TABLE 5.—*Comparative classifications of intrusive rocks in the South Park-Breckenridge region*

Ransome (1911)	Bryant and others (1980)	Rock types based on chemical analysis	Localities dated
Quartz monzonite porphyry	Porphyritic quartz monzonite	Quartz monzonite	1
Quartz monzonite	Quartz monzonite	Granodiorite	3
Monzonite porphyry	Monzonite	Quartz monzonite (7), granodiorite (2, 4, 5), and very minor potassic diorite.	2, 4, 5, 6, 7

Boreas Pass-South Park fault zone (fig. 8, localities 4 and 5). A small plug of monzonite porphyry located at the junction of the Middle and South Forks of the Swan River is intrusive into and has metamorphosed brecciated Precambrian rock along the Williams Range fault zone (fig. 8, locality 2).

The intrusive bodies predate some fault movements. A sill in the Benton Group west of Kenosha Pass is cut by faults that, if they are vertical, have displacements as much as 200 m (fig. 8). The west margin of the Bald Mountain sill is offset by faults. Lovering (1934) shows numerous faults, with displacements as great as 200 m, that cut the intrusive rocks near Breckenridge.

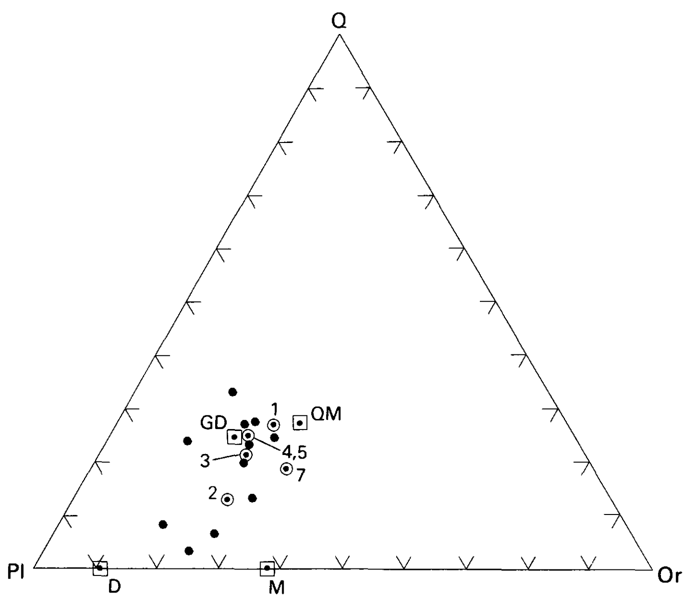


FIGURE 10.—Normative quartz-plagioclase-orthoclase diagram for intrusive rocks of the South Park-Breckenridge area. Based on chemical analyses from Ransome (1911), Muilenburg (1925), Phair and Jenkins (1975), and table 8, this paper. Circled points are analyses of rocks dated in this study; numbers indicate locality (fig. 8). Squares are averages for rock types from Nockolds (1954); D, diorite; M, monzonite; GD, granodiorite; QM, quartz monzonite.

SAMPLE LOCALITIES

We sampled each of the three major rock types for age determinations (table 5; figs. 8 and 9). One sample each of monzonite and quartz monzonite are from intrusives at or near the Williams Range fault. Locality 1 is in a sill of porphyritic quartz monzonite west of the Williams Range fault. Locality 2 (fig. 8) is in a small monzonite intrusive in the Pierre Shale along the fault zone. Dikes from the intrusive cut the fault zone, and brecciated Precambrian rock in the fault zone has been contact metamorphosed. Locality 3 is on the northeast margin of the Mt. Guyot plug near metamorphosed Pierre Shale and Dakota Sandstone west of the Williams Range fault. Localities 4 and 5 are in monzonite porphyry from the southeast margin of the Bald Mountain sill in the area where it cuts branches of the Boreas Pass-South Park fault zone. Locality 6 is in a thin sill of monzonite in the Pierre Shale. Thin section study indicates that the rock at locality 6 is similar to that at localities 4 and 5 but is much more altered.

AGE OF THE INTRUSIVE ROCKS

K-Ar and fission-track ages of minerals are shown in fig. 9 and table 4; analytical data are listed in tables 7 and 8 in the appendix.

Biotite ages from localities 1 through 3 are 44 to 55 m.y., but fission-track ages of zircon from these same localities are 35-38 m.y. Thus there are discrepancies of 9 m.y., 8 to 13 m.y., and 6 m.y. between the K-Ar ages of the biotite and the fission-track ages of the zircon in samples from localities 1, 2, and 3 respectively. Ages were determined for biotite from three different separates of the samples from localities 1 and 2 in an attempt to resolve these discrepencies. To confirm the zircon ages, a second determination was made from the original separate from the sample of locality 2, and a third was made on a new separate from the same sample.

To further test the validity of the discordant ages for samples from locality 2, we dated a zircon from contact-metamorphosed brecciated Precambrian rock (locality 2, sample 466) adjacent to the intrusive. The age of 38.2 m.y. is the same as that obtained from zircons from the intrusive rock. Fission-track ages of apatite (Bryant and Naeser, 1980) from Precambrian rocks 1-2 km from the exposed plutons are older than the zircon ages from the intrusive rocks; thus the discrepancy between zircon and biotite ages cannot be due to regional heating or cooling 35-38 m.y. ago.

Excellent agreement of ages of about 41 m.y. was obtained from biotite, zircon, and apatite from the Bald Mountain sill at locality 5 (table 4). A second biotite determination from locality 5 was made on an inclusion, and it agrees well with those from the sill, within the respective limits of analytical uncertainty. The sample from locality 4 is from the same sill, about 2 km from locality 5. The two samples are petrographically similar (table 6), except that the rock at locality 4 is somewhat more altered than that at 5. Ages of sphene and apatite from locality 4 agree with the ages from locality 5, but the zircon is about 5 m.y. younger at 4 than at 5. We conclude that the Bald Mountain sill was emplaced about 41 m.y. ago in the late Eocene. A small sill at locality 6, 6 km to the southeast, has the same age.

The general agreement of ages of apatite, sphene, and zircon from the intrusive rocks indicates that the rock cooled quickly, for the annealing temperature of apatite is much lower than that of sphene and zircon (Naeser and Faul, 1969). A notable exception is from locality 7, where the apatite age of 56.4 m.y. is older than the zircon age of 37.6 m.y. In that sample, however, the apatite has many crystal defects that may have been counted as fission tracks.

The authors have found, in many previous investigations where both fission-track and K-Ar ages were determined, that agreement of K-Ar and fission-track ages is usually good, except where a thermal event has caused loss of radiogenic argon and (or) annealing of fission tracks (Cunningham and others, 1977; Naeser and others, 1977). Following such an event, the fission-track ages of sphene are usually similar to the K-Ar age of biotite, which, in turn, is usually greater than the fission-track age of zircon, which is greater than the fission-track age of apatite (Harrison and others, 1979). In the present study, however, the K-Ar and fission-track ages for minerals from localities 1 through 3 indicate a rather unusual situation. The K-Ar biotite ages are significantly older than the fission-track zircon ages of sphene, zircon, and apatite. The fission-track ages of these three minerals are concordant. It seems illogical that a thermal event, after emplacement, could anneal fission tracks in the zircons without resetting the apatite ages in nearby Precambrian country rock. Furthermore, it seems unreasonable that 5 to 10 m.y. could have elapsed between the time biotite became a closed system, and the time that zircon fission tracks were annealed, without producing marked discrepancies in fission-track ages of sphene, zircon, and apatite.

Based on the information given above, the most logical explanation is that there is excess radiogenic argon in the biotite. It appears that the biotite from locality 1 has a nearly constant amount of excess argon distributed throughout the biotite grains, resulting in good agreement for triplicate argon determinations (table 7). Even the third biotite separate, which has a discernible hornblende impurity (indicated by the K_2O content, table 7, appendix), has a K-Ar age concordant with those of the two clean biotite separates. The ages of biotite from locality 2, however, indicate that excess argon varies in amount among individual biotite grains. Again, a significant amount of impurity in the third biotite sample run from locality 2 did not produce a biotite age greater than that determined for one of the clean samples. Therefore, excess argon does not appear to be concentrated in the impurities, but must be partitioned among the mafic minerals in an approximately even manner.

In line with this reasoning, the fission-track ages are accepted as the ages of emplacement of the plutons at localities 1 through 3, which are 35, 37, and 38 m.y., respectively, or early Oligocene.

The Montezuma stock, northeast of Breckenridge (fig. 5), has a biotite K-Ar age, a Rb-Sr biotite whole-rock age, and zircon and apatite fission-track ages that are all concordant at 39 m.y. (McDowell, 1971; Simmons and Hedge, 1978; A. A. Bookstrom and C. W. Naeser, written communication, 1979). A zircon fission-track age of 35 m.y. has been obtained from a satellitic intrusion just to the south (Cunningham and others, 1977). These ages are similar to those obtained from rocks in the South Park-Breckenridge region.

K-Ar ages of 43-45 m.y. cannot be dismissed, however, for some intrusive rocks in this region. Simmons and Hedge (1978) obtained a Rb-Sr biotite whole-rock age of 45 m.y. from a sill of porphyritic quartz monzonite at Swan Mountain, north of Breckenridge. V. E. Surface of Climax Molybdenum Co. obtained biotite K-Ar ages of 35-47 m.y. from quartz monzonite porphyry of the Humbug stock in the Tenmile Range, about 10-km west of Breckenridge (Marvin and others, 1974). In the Humbug stock, fission-track ages of zircon also are younger than the biotite K-Ar ages (M. A. Kuntz and C. W. Naeser, oral communication, 1978).

Fission-track ages of zircon and sphene are concordant with K-Ar and Rb-Sr ages of biotite in the Twin Lakes stock in the Sawatch Range (fig. 7) (Moorbath and others, 1967; Obradovich and others, 1969; Marvin and others, 1974; and Marvin and Dobson, 1979). The main part of the Twin Lakes stock was intruded about 45 m.y. ago. A younger granitic intrusion that cuts the main Twin Lakes stock (Wilshire, 1969) yields zircon and sphene ages of about 35 m.y., about 10 m.y. younger than the main part of the Twin Lakes stock. This age is similar to that of a stock intruding the Grizzly Peak cauldron in the Sawatch Range about 10 km farther west (Obradovich and others, 1969). Apatite fission-track ages from the Twin Lakes stock, the younger intrusion that cuts the Twin Lakes stock, and the Precambrian rocks on the west margin of the Sawatch Range all are less than 29 m.y. old and are all related to later uplift and cooling of the mountain block (Bryant and Naeser, 1980).

Relatively few ages in the range 45–55 m.y. have been obtained on rocks in the Colorado mineral belt, but a few are reported from the northeast end of the mineral belt (Marvin and others, 1974).

The number of intrusive rocks in the mineral belt that have been dated as Eocene suggests that the former idea of distinct Laramide and mid-Tertiary intrusive events is no longer acceptable.

It also is now clear that neither proximity nor similarity in chemistry and (or) mineralogy implies contemporaneity of intrusions. This point is well illustrated by the difference in the ages of the Lincoln Porphyry (64 m.y.) near Leadville (Pearson and others, 1962; McDowell, 1971) and the petrographically and texturally similar coarse-grained porphyritic quartz monzonite of the Breckenridge district at locality 1, which has an age of about 35 m.y. The latter was correlated with the Lincoln Porphyry by Ransome (1911) and Lovering (1934).

In some areas of the mineral belt in the Front and Sawatch Ranges, rhyolites in small bodies and granites in larger bodies have been dated as being as young as late Oligocene or early Miocene, (Taylor and others, 1968; Naeser and others, 1973; Schassberger, 1972; Van Alstine, 1969; Limbach, 1975). Since dikes and plugs of rhyolite commonly are altered and, consequently, not datable by some methods, the distribution of these younger, more silicic rocks is imperfectly known. However, they are volumetrically less significant than the early Oligocene and late Eocene intrusives.

Traditional concepts of the igneous history of the mineral belt, involving either an orderly progression of intrusive events from southwest to northeast or two well-defined intrusive events, seem to be yielding to the idea of a more continuous period of intrusion spanning the period from 70 to 25 m.y. ago. Geophysical studies suggest that the mineral belt is underlain by a batholith (Tweto and Case, 1972; Isaacson and Smithson, 1976), which may be a composite batholith with a long and complex history. In some areas, however, such as the San Juan Mountains, most of the magma that formed the top of the batholith apparently was emplaced during Oligocene time.

EXTRUSIVE ROCKS

In the Antero syncline, in the southwestern part of South Park, andesite flow breccia apparently occurs in a northwest-trending paleovalley (fig. 8). The Wall Mountain Tuff, about 36 m.y. old, occurs in shallow channels carved into the andesite. These volcanic rocks are overlain by the Antero Formation of Oligocene age and the Wagontongue Formation of Miocene age. Much of the folding of the syncline is younger than the Wagontongue Formation. The age of the andesite flow breccia (locality 8, table 4 and fig. 8) is about 40 m.y. (average of biotite K-Ar age of 38 m.y. and zircon and apatite fission-track ages of 42 m.y.). This age indicates that the flow is contemporaneous with some of the intrusive rocks discussed above but is older than the Wall Mountain Tuff and the stratigraphically higher Buffalo Peaks Andesite and Badger Creek Tuff (Epis and Chapin, 1974; Sanders and others, 1976). The intrusive bodies nearest to locality 8 are 10 km to the northwest, but they have not been dated. Stark and others (1949) classified these intrusives as quartz monzonite. Chemical analysis of the andesite flow breccia (field no. 430a, table 9) shows that it is much more siliceous than is apparent in outcrop or thin section and is a quartz latite. The nearby intrusives therefore are a reasonable source for the flow breccia.

Southeast of Kenosha Pass (fig. 8), an andesitic ash flow (field No. 430a, mapped as andesite but shown to be a rhyodacite by chemical analysis (table 9)) occupies a southeast-trending paleovalley, the bottom of which is 50 to 150 m below a widespread erosion surface on Precambrian rocks east of South Park. This surface, known as the Elkhorn surface, has been correlated with a widespread erosion surface of Eocene age in the region to the south (Scott, 1975; Epis and Chapin, 1975). A fission-track age of 36 m.y. on zircon from the volcanic rock in the paleovalley is similar to ages obtained from the intrusive rocks to the west. The trend of the paleovalley, however, suggests that the ash flow in it is an outflow from a vent in the area near the Montezuma stock, where the intrusives are also of that age.

AGE OF MAIN DEFORMATION IN SOUTH PARK AND ALONG THE MARGIN OF THE FRONT RANGE UPLIFT

Our data on the age of rocks in the South Park-Breckenridge region put some constraints on the timing of deformation in the region. The Boreas Pass-South Park fault zone, northwest of Como, is cut by the Bald Mountain sill (localities 4 and 5, fig 8). Latest major movements on this fault zone occurred after deposition of the South Park Formation in the Paleocene and before emplacement of that sill about 41 m.y. ago. This fault zone also had large pre-Laramide movements and formed the front of a late Paleozoic range. Boulder conglomerates in the uppermost part of the South Park Formation, adjacent to the Elkhorn fault, were derived from source areas east of the Elkhorn fault. They indicate that uplift and probably faulting along the west margin of the Front Range occurred during the earliest Eocene.

Ages of rocks from localities 2 and 3, farther north, put a limit of middle Eocene on the minimum age of movement of the Williams Range fault. A connection between the Williams Range and Elkhorn faults in the northern part of South Park is not exposed and is inferred on the basis of geophysical data (Barker and Wyant, 1976). In the absence of a known connection with the Elkhorn fault, no inference can be made about the earliest possible time of movement on the Williams Range fault except at its northernmost exposures 90 km to the northwest (fig. 7). There, earliest movement was very Late Cretaceous, before deposition of the Middle Park Formation, a basin fill analogous to the South Park Formation. (Izett and Barclay, 1973). However, to the east, the Middle Park Formation is folded with the Cretaceous rocks and cut by faults (Izett 1968; Taylor, 1975), indicating a time relation between early Tertiary deposition and deformation similar to that in South Park.

In Paleocene igneous rocks along the east side of the Front Range uplift between Golden and Lyons, Hoblitt and Larson (1975) found paleomagnetic evidence that Laramide deformation there was older to the north than to the south. Perhaps this relationship is also true along the west side of the Front Range.

Between Denver and Colorado Springs, several faults cut the Upper Cretaceous and Paleocene Denver Formation and the Paleocene and Eocene Dawson Arkose at the eastern margin of the Front Range (fig. 7). Because the Denver and the Dawson are mostly structurally concordant with the underlying Cretaceous rocks, the structural relief at the present mountain front is due to post-Paleocene faulting. Soister (1978) and Soister and Tschudy (1978) have recently found that some of the Dawson Arkose above a well-developed soil horizon is of Eocene age, but as yet it has not been possible to map this soil zone and determine relations between rocks above and below it along the mountain front. However, north of Colorado Springs, lower Oligocene rocks (Wall Mountain Tuff; Castle Rock Conglomerate) that occur on the highest hills on the margin of the Great Plains can be projected westward to the range front. Then, if we assume that a well-developed surface on the crest of the Rampart Range, just west of the margin of the Front Range, is approximately at the level of an erosion surface of Eocene age (Scott, 1975) and about on grade with deposits laid down in the early Oligocene, we can infer about 600 m of offset by post-Oligocene movement along the range front fault. Cross sections and stratigraphic relations along the mountain front in that area suggest post-Paleocene but pre-Oligocene displacement of as much as 3 km along the same fault. Much of this displacement may have been contemporaneous with the Eocene deformation of the South Park Formation on the west side of the Front Range uplift.

IMPLICATIONS OF AGES FOR THE EXTENT OF THE EOCENE EROSION SURFACE

The highest peaks between South Park and Middle Park are composed of intrusive igneous rocks of latest Eocene and earliest Oligocene age, which crop out at altitudes as great as 4,170 m, but no extrusive volcanic rocks are known from that area. Extrusive rocks of this age were deposited in shallow valleys in the Elkhorn surface on the east side of South Park, and these are preserved at 2,900-m altitude. The Elkhorn surface correlates with the Eocene erosion surface that is so widespread to the south and east (Scott, 1975; Epis and Chapin, 1975). If we assume a minimum cover of 500 to 1,000 m on the latest Eocene and earliest Oligocene intrusive rocks at the time of intrusion, a postulated Eocene erosion surface west of South Park would presently be at an altitude of about 5,000 m. If such an erosional surface did exist west of South Park in the area underlain by intrusive rocks, substantial vertical displacement of that area since the middle Tertiary is required. Bryant and

others (1980), Stark and others (1949), and Barker and Wyant (1976) have not detected any major fault bounding the west side of the park; the mapped faults trend north-northwesterly and cross the high country of the continental divide underlain by the intrusive rocks. Perhaps the deformation that produced this apparent vertical offset was accomplished by warping rather than high-angle faulting, or alternatively, there may have been high mountains in Eocene time rising above the broad lowland represented by the Elkhorn surface.

REFERENCES CITED

Barker, Fred, and Wyant, D. G., 1976, Geologic map of the Jefferson quadrangle, Park and Summit Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1345.

Brown, R. W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: U.S. Geological Survey Professional Paper 375, 119 p.

Bryant, Bruce, McGrew, L. W., and Wobus, R. A., 1980, Geologic map of the Denver 1° × 2° quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1163.

Bryant, Bruce, and Naeser, C. W., 1980, The significance of fission-track ages of apatite in relation to the tectonic history of the Front and Sawatch Ranges, Colorado: Geological Society of America Bulletin, v. 91, no. 3, p. 156-164.

Cunningham, C. G., Naeser, C. W., and Marvin R. F., 1977, New ages for intrusive rocks in the Colorado mineral belt: U.S. Geological Survey Open-File Report 77-573, 7 p.

Epis, R. C., and Chapin, C. E., 1974, Stratigraphic nomenclature of the Thirtynine Mile volcanic field, central Colorado: U.S. Geological Survey Bulletin 1395-C, 23 p.

——— 1975, Geomorphic and tectonic implications of the post-Laramide, Late Eocene erosion surface in the Southern Rocky Mountains, *in* Curtis, B. F., ed. Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 45-74.

Harrison, T. M., Armstrong, R. L., Naeser, C. W., and Harakal, J. E., 1979, Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia: Canadian Journal of Earth Science, v. 16, no. 3 (part 1), p. 400-410.

Hart, S. R., 1960, A study of mineral ages in a contact metamorphic zone, *in* Variations in isotopic abundances of strontium, calcium, and argon and related topics: Cambridge, Mass., Massachusetts Institute of Technology, Department of Geology and Geophysics, NYO-3941, 8th Annual Progress Report for 1960, U.S. Atomic Energy Commission Contract AT (30-1)-1381, p. 131-154.

Hart, S. R., 1964, The petrology and isotopic mineral age relations of a contact zone in the Front Range, Colorado: Journal of Geology, v. 72, p. 493-525.

Hoblitt, R., and Larson E., 1975, Paleomagnetic and geochronologic data bearing on the structural evolution of the northeastern margin of the Front Range, Colorado: Geological Society of America Bulletin, v. 86, no. 2, p. 237-242.

Isaacson, L. B., and Smithson, S. B., 1976, Gravity anomalies and granite emplacement in west-central Colorado: Geological Society America Bulletin, v. 87, no. 1, p. 22-28.

Izett, G. A., 1968, Geology of the Hot Sulphur Springs quadrangle: U.S. Geological Survey Professional Paper 586, 79 p.

Izett, G. A. and Barclay, C. S. V., 1973, Geologic maps of the Kremmling quadrangle, Grand Co., Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1115.

King, P. B., and Beikman, H. M., 1974, Geologic map of the United States: U.S. Geological Survey [1975].

Limbach, Fred, 1975, The geology of the Buena Vista area, Chaffee County, Colorado: Colorado School of Mines M.S. thesis, 98 p.

Lipman, P. W., Steven, T. A., and Mehnert, H. H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geological Society America Bulletin, v. 81, p. 2329-2352.

Lovering, T. S., 1934, Geology and ore deposits of the Breckenridge mining district, Colorado: U.S. Geological Survey Professional Paper 176, 64 p.

Lovering, T. S., and Goddard E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geological Survey Professional Paper 223, 319 p.

McDowell, F. W., 1971, K-Ar ages of igneous rocks from the western United States: Isochron/West, no. 2, p. 1-16.

Marvin, R. F., and Dobson, S. W., 1979, Radiometric ages: Compilation B, U.S. Geological Survey: Isochron/West, no. 26, 32 p.

Marvin, R. F., Young, E. J., Mehnert, H. H., and Naeser, C. W., 1974, Summary of radiometric age determination on Mesozoic and Cenozoic igneous rocks and uranium and base metal deposits in Colorado: Isochron/West, no. 11., 41 p.

Moorbath, S., Hurley, P. M., and Fairbairn, H. W., 1967, Evidence for the origin and age of some mineralized Laramide intrusives in the southwestern United States from strontium isotope and rubidium-strontium measurements: Economic Geology, v. 62, p. 226-236.

Muilenburg, G. A., 1925, Geology of the Tarryall district, Park County, Colorado: Colorado Geological Survey Bulletin 31, 64 p.

Naeser, C. W., and Faul, Henry, 1969, Fission-track annealing in apatite and sphene: Journal of Geophysical Research, v. 74, p. 705-710.

Naeser, C. W., Hurford, A. J., and Gleadow, A. O. W., 1977, Reply *to comment by* G. A. Wagner *on* Fission-track dating of pumice from the KBS tuff, East Rudolf, Kenya: Nature, no. 5612, p. 649.

Naeser, C. W., Izett, G. A., and White, W. H., 1973, Zircon fission-track ages from some middle Tertiary igneous rocks in northwestern Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 5, no. 6, p. 498.

Naeser, C. W., Johnson, N. M., and McGee, V. E., 1978, A practical method of estimating the standard error of age in the fission-track dating method, *in* Zartman, R. E., ed., Short papers of the fourth international conference of geochronology, cosmochronology, and isotope geology: U.S. Geological Survey Open-File Report 78-701, p. 303-304.

Nockolds, S. R., 1954, Average chemical composition of some igneous rocks: Geological Society of America Bulletin, v. 65, no. 10, p. 1007-1032.

Obradovich, J. D., Mutschler, F. E., and Bryant, Bruce, 1969, Potassium-argon ages bearing on the igneous and tectonic history of the Elk Mountains and vicinity—A preliminary report: Geological Society of America Bulletin, v. 80, no. 9, p. 1749-1756.

Pearson, R. C., Tweto, Ogden, Stern, T. W., and Thomas, H. H., 1962, Age of Laramide porphyries near Leadville, Colorado *in* Short papers in geology and hydrology: U.S. Geological Survey Professional Paper 450-C, p. C78-C80.

Phair, George, and Jenkins, L. B., 1975, Tabulation of uranium and thorium data on the Mesozoic-Cenozoic intrusive rocks of known chemical composition in Colorado: U.S. Geological Survey Open-File Report 75-501, 57 p.

Pride, D. E., and Robinson, G. S., 1978, Multiple intrusion and hydrothermal activity, eastern Breckenridge mining district, Summit County, Colorado: Geological Society of America Bulletin, v. 89, p. 866-874.

Ransome, F. L., 1911, Geology and ore deposits of the Breckenridge district, Colorado: U.S. Geological Survey Professional Paper 75, 187 p.

Sanders, G. F., Jr., Scott, G. R., and Naeser, C. W., 1976, The Buffalo Peaks Andesite of central Colorado: U.S. Geological Survey Bulletin 1405-F, 8 p.

Sawatzky, D. L., 1967, Tectonic style along the Elkhorn thrust, eastern South Park and western Front Range, Colorado: Colorado School of Mines D. Sc. thesis, 206 p.

Schassberger, H. T., 1972, K-Ar dates on intrusive rocks and alteration associated with molybdenum mineralization at Climax and Urad, Colorado, and Questa, New Mexico: Isochron/West, no. 3, p. 29.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, *in* Curtis, B. F., ed. Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 227-248.

Scott, G. R., Taylor, R. B., Epis, R. C., and Wobus, R. A., 1978, Geologic map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1022.

Shapiro, Leonard, 1975, Rapid analysis of silicate, carbonate, and phosphate rocks—Revised edition: U.S. Geological Survey Bulletin 1401, 76 p.

Simmons, E. C., and Hedge, C. E., 1978, Minor element geochemistry and Sr-isotopes of Tertiary stocks, Colorado Mineral Belt: Contributions to Mineralogy and Petrology, v. 67, p. 379-396.

Singewald, Q. D., 1942, Stratigraphy, structure, and mineralization in the Beaver-Tarryall area, Park County, Colorado: U.S. Geological Survey Bulletin 928-A, 44 p.

——1951, Geology and ore deposits of the upper Blue River area, Summit County, Colorado: U.S. Geological Survey Bulletin 970, 74 p.

Soister, P. E., 1978, Stratigraphy of uppermost Cretaceous and lower Tertiary rocks of the Denver basin, *in* Pruit, J. D., and Coffin, P. E., eds., Energy resources of the Denver basin: Denver, Rocky Mountain Association of Geologists, p. 223-229.

Soister, P. E., and Tschudy, R. H., 1978, Eocene rocks in the Denver basin, *in* Pruitt J. D., and Coffin, P. E., eds., Energy resources of the Denver basin: Denver, Rocky Mountain Association of Geologists, p. 231-235.

Spurr, J. E., and Garrey, G. H., 1908, Economic geology of the Georgetown quadrangle, Colorado *with* General geology by Sidney H. Ball: U.S. Geological Survey Professional Paper 63, 422 p.

Stark, J. T., Johnson, J. H., Behre, C. H., Jr., Powers, W. E., Howland, A. L., Gould, D. B., and others, 1949, Geology and origin of South Park, Colorado: Geological Society of America Memoir 33, 188 p.

Taylor, R. B., 1975, Geologic map of the Bottle Pass quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1224.

Taylor, R. B., Theobald, P. K., and Izett, G. A., 1968, Mid-Tertiary volcanism in the central Front Range, Colorado, *in* Epis, R. C., ed., Cenozoic volcanism in the southern Rocky Mountains: Colorado School of Mines Quarterly, v. 63, no. 3, p. 39-50.

Tweto, Ogden, and Case, J. E., 1972, Gravity and magnetic features as related to geology in the Leadville 30-minute quadrangle, Colorado: U.S. Geological Survey Professional Paper 726-C, 31 p.

Tweto, Ogden, Moench, R. H., and Reed, J. C., Jr., 1978, Geologic map of the Leadville 1°×2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-999.

Van Alstine, R. E., 1969, Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado: U.S. Geological Survey Professional Paper 626, 52 p.

Wilshire, H. G., 1969, Mineral layering in the Twin Lakes Granodiorite, Colorado, *in* Igneous and metamorphic geology—A volume in honor of Arie Poldervaart: Geological Society America Memoir 115, p. 235-261.

Wyant, D. G., and Barker, Fred, 1976, Geologic map of the Milligan Lakes quadrangle: Park County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1343.

Young, E. J., 1972, Laramide-Tertiary intrusive rocks of Colorado: U.S. Geological Survey Open-File Report, 206 p.

TABLES 6–9

TABLE 6.—*Location and description of dated and analyzed*

Loc. No.	Field No.	North Latitude	West Longitude	Locality description	Quadrangle	Rock type
				Intrusive rocks		
1	223	39°30'19"	105°57'47"	Knob with spot elevation 11,212, 500 m NE. of Brewery Hill. Sill(?) in Pierre Shale.	Keystone---	Porphyritic hornblende-biotite quartz monzonite.
2	222	39°29'33"	105°56'31"	Small cliff 300 m S. 22° E. of spot elevation 9977 on sharp corner on Middle Fork Swan River road. Small plug in Pierre Shale and Williams Range fault.	Boreas Pass	Pyroxene-bearing hornblende-biotite granodiorite.
	466	39°29'31"	105°56'14"	3291-m altitude on ridge between Middle and South Forks Swan River. Williams Range fault zone.	-----do----	Brecciated and contact metamorphosed gneiss.
3	74	39°27'34"	105°55'44"	Small cliff at 3672-m altitude on E. shoulder of Mt. Guyot 1 km N. 80° W. of Georgia Pass. Stock in Pierre Shale 120 m from Williams Range fault.	-----do----	Biotite quartz monzonite.
4	233	39°21'37"	105°56'12"	Cut in abandoned railroad grade 500 m N. 81° W. of BM 10,576 at Halfway Gulch. Large irregular sill in Morrison Formation to lower Pierre Shale.	Como-------	Porphyritic biotite granodiorite.
5	503	39°20'40"	105°55'37"	Cut in old railroad grade and road to Boreas Pass. 300 m S. 24° E. of Peabodys site. Same intrusive as sample 4.	-----do----	Porphyritic hornblende-biotite quartz monzonite.
	503a					Biotite-rich xenolith--
6	502	39°17'54"	105°53'50"	Roadcut on U.S. Highway 285, 2 km S. 15° W. of roundhouse in Como. Probable sill in Pierre Shale.	-----do----	Altered porphyritic quartz monzonite.
7	328	39°25'19"	105°50'04"	Jefferson Hill, 3100-m altitude on southwest side. Sill in the Benton Group.	Jefferson--	Hornblende-biotite andesite porphyry.
				Extrusive rocks		
8	430a	39°00'48"	105°53'55"	Sec. 9, T. 12 S., R. 75 W., 550 m E. of SW. corner and 60 m N. of section line. Andesite underlying Wall Mountain Tuff.	Garo-------	Quartz-bearing andesite flow breccia.
9	420	39°22'44"	105°43'38"	Sec. 1, T. 8 S., R. 75 W., on centerline of SW 1/4 and 300 m N. of S. boundary. Fills paleovalley in Elkhorn surface.	Mt. Logan--	Andesitic ash flow tuff

samples from the South Park-Breckenridge region

Loc. No.	Field No.	Sample description	Accessory minerals	Chemical analysis of similar rock
		Intrusive rocks		
1	223	Light-gray rock containing quartz phenocrysts to 0.5 mm, biotite to 2 mm, plagioclase to 0.5 mm, and widely scattered potassic feldspar to 1 cm. Euhedral sodic andesine and calcic oligoclase with normal zoning, somewhat resorbed euhedral quartz, euhedral biotite, and small, euhedral, light-green, locally chloritized amphibole 0.2 to 0.3 mm. A matrix of quartz and potassic feldspar with a grain size of 0.05 to 0.1 mm.	Sphene, apatite, zircon, and opaques.	Ransome (1911, p. 45, No. 1).
2	222	Euhedral to subhedral andesine to labradorite to 1.5 mm long; anhedral, partly interstitial quartz to 0.2 mm in diameter; interstitial potassic feldspar; very light green anhedral monoclinic pyroxene intergrown with biotite; light-green euhedral to subhedral amphibole to 1 mm long partly intergrown with biotite and pyroxene; and anhedral to subhedral biotite to 1 mm long.	Opaque mineral, apatite, and zircon.	Table 9.
	466	Fragments of quartz as large as 4 mm in diameter, fractured, partly altered garnet and feldspar in a fine-grained matrix of quartz and feldspar, and postkinematic brown biotite.	Epidote, sericite, zircon, and opaque minerals.	Not available.
3	74	Subhedral to euhedral sodic andesine to 1.5 mm long with normal and oscillatory zoning, anhedral cryptoperthitic potassic feldspar to 3 mm, interstitial quartz 0.3 to 1 mm, subhedral brown biotite 0.5 mm (average) to 1.2 mm (maximum), and a few grains of olive-green hornblende 0.1 to 0.6 mm long, partly altered to biotite.	Opaque minerals, apatite, and zircon.	Ransome (1911, p. 58).
4	233	Euhedral phenocrysts of sodic andesine to 2 mm long, partly altered to sericite and carbonate; euhedral to anhedral resorbed phenocrysts of quartz to 1.5 mm; euhedral, partly chloritized phenocrysts of brown biotite to 1 mm in a matrix of quartz and feldspar with a grain size less than 0.05 mm.	----do----------	Muilenburg (1925, p. 36).
5	503	Partly resorbed phenocrysts of andesine as long as 2 mm, somewhat resorbed euhedral quartz to 1 mm, euhedral biotite to 1.4 mm, euhedral light-green hornblende to 0.6 mm, and sanidine to 3 mm in a matrix of quartz and feldspar with a grain size of 0.02 mm.	Apatite, allanite, zircon, and opaque minerals. Some carbonate from alteration of plagioclase.	Not available.
6	502	Phenocrysts of partly resorbed quartz to 3 mm; plagioclase as much as 1.3 mm in diameter altered to albite and carbonate; and chlorite after biotite and hornblende in a fine-grained matrix of quartz, altered feldspar, chlorite, and carbonate.	Apatite, allanite, and opaque minerals.	Do.
7	328	Euhedral phenocrysts of biotite to 2 mm, phenocrysts and glomerophenocrysts of andesine with oscillatory zoning in a sodic trend to 5 mm in diameter, and hornblende and monoclinic pyroxene in a very fine grained matrix of feldspar and quartz.	Opaque minerals, apatite, and zircon.	Table 9.
		Extrusive rocks		
8	430a	Phenocrysts and glomerophenocrysts of andesine to 5 mm in diameter, of biotite to 2 mm, hornblende to 1 mm, and quartz as fragments as much as 2.5 mm in diameter, all set in a fine-grained matrix.	Opaque minerals, apatite, and zircon.	Table 9.
9	420	Euhedral to anhedral cyrstals and crystal fragments of andesine, quartz, biotite, and green hornblende in a fine-grained matrix of devitrified glass.	----do----------	See sample No. 421, table 9.

TABLE 6.—*Location and description of dated and analyzed*

Loc. No.	Field No.	North Latitude	West Longitude	Locality description	Quadrangle	Rock type
				South Park Formation		
10	W-1-75	39°13'49"	105°48'31"	T. 9 S., R. 75 W., 120 m S. of NE. corner sec. 31. About 1600 m above base of South Park Formation.	Elkhorn----	Hornblende-biotite-quartz-plagioclase crystal tuff.
11	150	39°15'27"	105°49'32"	Borrow pit on Elkhorn road 1020 m SW. of BM 9405 on Elkhorn Road. Link Springs Tuff Member of the South Park Formation.	Milligan Lakes.	Hornblende-biotite-plagioclase-quartz crystal tuff.
12	444	39°08'58"	105°48'55"	T. 10 S., R. 75 W., 200 m S. 51° E. from center sec. 30. Base of South Park Formation.	Elkhorn----	Felsic crystal tuff----
13	325	39°17'51"	105°51'10"	T. 9 S., R. 76 W., 120 m N. 60° E. of center of sec. 2. Unaltered lens in andesite about 160 m above base of formation.	Milligan Lakes.	Biotite-hornblende andesite flow.
				Analyzed samples closely related to rocks dated in the study		
14	323	39°15'17"	105°55'01"	Stratigraphically lowest outcrop at 2993-m altitude 122 m N. 37° E. of spring. Sawatzky (1967) gives K-Ar whole-rock age from this outcrop.	Como-------	Andesite--------------
15	421	39°22'11"	105°42'07"	2993-m altitude 167 m N. 70° E. of junction on Lost Park Road marked 9733 on map. Same unit as dated rock from locality 9.	Observatory Rock.	Andesitic ash flow-----

samples from the South Park-Breckenridge region—Continued

Loc. No.	Field No.	Sample description	Accessory minerals	Chemical analysis of similar rock
		South Park Formation		
10	W-1-75	Fragments of quartz 0.1 to 1.5 mm, andesine 0.1 to 1.5 mm, biotite to 1 mm, and hornblende to 0.4 mm in a matrix of devitrified glass containing some pumice fragments. One fragment of feldspathic sandstone was seen. X-ray study indicates the glass has been converted to clinoptilolite.	Apatite, zircon, and opaque minerals.	Table 9.
11	150	Biotite to 0.5 mm in diameter, dark-green to brownish-green hornblende to 0.3 mm, andesine 0.2 to 0.5 mm, quartz, and partly devitirified glass. X-ray study shows the glass has been replaced by clinoptilolite.	----do-----------	Do.
12	444	Crystal fragments of quartz 0.1 to 1 mm, sodic andesine 0.1 to 1 mm, biotite to 1 mm, and green to brown hornblende in a matrix of pumice and devitrified glass. X-ray study indicates much of the devitrified glass is clinoptilotite.	----do-----------	Do.
13	325	Euhedral, dark-greenish-brown hornblende 0.3 to 3 mm, andesine 0.2 to 2 mm with delicate oscillatory zoning, biotite to 1 mm, anhedral quartz to 0.5 mm, and light-green monoclinic pyroxene in a matrix of devitrified glass. Quartz in amygdules.	Epidote, opaque, and apatite.	Do.
		Analyzed samples closely related to rocks dated in this study		
14	323	Euhedral phenocrysts of reddish-brown hornblende 0.15 to 1.5 mm long, partly altered to greenish-brown hornblende, and of altered plagioclase 0.15 to 2 mm. Matrix of altered glass contains a few aggregates of quartz.	Opaque minerals and apatite.	Table 9.
15	421	Fragments of andesine to 2 mm, quartz to 1.5 mm, euhedral to subhedral biotite to 1.5 mm, and greenish-brown hornblende with a partly zeolitized glassy matrix.	Zircon, apatite, opaque minerals and carbonate.	Do.

TABLE 7.—*Analytical data for K-Ar ages of igneous rocks in the South Park-Breckenridge region*

[All determinations made on biotite; some additional minerals intermixed as noted below. ^{40}K $\lambda_{\epsilon}=0.581\times10^{-10}/yr$. $\lambda_{\beta}=4.962\times10^{-10}/yr$, Atomic abundance $^{40}K=1.167\times10^{-4}$ atom/atom K. Potassium determinations made with an Li internal standard. Analysts: R. F. Marvin, H. H. Mehnert, and Violet Merritt]

Loc. No.	Field No.	K_2O (percent)	Radiogenic ^{40}Ar Moles/g ($\times10^{-10}$)	Radiogenic ^{40}Ar Percent of total Ar	Age (m.y.) ±2σ
1	223	8.71, 8.69	5.689	85	44.8±1.5
		9.01, 8.93	5.634	74	43.1±1.5
		[1] 8.17, 8.20	5.252	72	44.0±1.5
2	222	8.42, 8.42	6.214	87	50.6±1.7
		8.70, 8.65	5.754	87	45.5±1.5
		[2] 6.07, 6.10	4.361	87	49.1±1.6
3	74	8.57, 8.61	5.511	89	44.0±1.5
5	503	[3] 2.57, 2.57	1.524	50	40.7±1.4
	503a	7.79, 7.76	4.896	78	43.2±1.5
8	430a	7.66, 7.64	4.211	77	37.8±1.3
9	W-1-75	3.90, 3.95	3.238	45	56.3±1.9
		3.99, 3.90			
10	150	8.11, 8.07	7.075	80	59.7±2.0
11	444	8.26, 8.30	7.952	92	65.5±2.2

[1] Biotite mixed with minor hornblende.
[2] Biotite mixed with hornblende.
[3] Biotite mixed with minor chlorite and hornblende.

TABLE 8.—*Analytical data for fission-track ages of igneous rocks in the South Park-Breckenridge region*

[Constants: λ_f=7.03×10^{-17}yr^{-1}. Analyst C. W. Naeser. Number of tracks counted is given in parentheses]

Loc. No.	Field No.	Lab No. DF-	Mineral	Fossil-track density[1] (ρ_s) (10^6 tracks/cm^2)		Induced-track density[1] (ρ_i) (10^6 tracks/cm^2)		Neutron flux (ϕ) (10^{15} n/cm^2)	Age (±2σ) (m.y.)	Number of grains	Uranium content (ppm)
1	223	592	Zircon	10.4	(723)	20.4	(700)	1.09	35.1± 3.6	3	570
2	222	817	---do--	6.08	(1188)	9.00	(943)	1.02	38.3± 1.8	19	290
		817	---do--	3.39	(392)	5.32	(308)	.965	36.6± 2.0	6	290
		841	---do--	5.22	(628)	8.44	(508)	.980	36.2± 1.6	6	275
	466	1504	---do--	5.55	(719)	8.76	(568)	1.01	38.2± 1.8	6	250
3	74	597	Sphene	5.93	(1456)	11.12	(1364)	1.27	40.4± 1.7	6	280
		588	Zircon	3.61	(852)	6.87	(795)	1.18	37.9± 1.6	6	190
		509	Apatite	.243	(113)	.387	(118)	1.13	42.7± 8.2	50	11
4	233	598	Sphene	2.10	(670)	3.92	(626)	1.25	39.9± 2.0	6	100
		594	Zircon	5.56	(1055)	10.68	(1014)	1.14	35.5± 1.4	6	300
		595	Apatite	.144	(134)	.238	(220)	1.13	41.1±10.	50	6.8
5	503	1802	Zircon	7.76	(1149)	12.30	(911)	1.07	40.3± 1.8	6	330
		1803	Apatite	.159	(331)	.239	(497)	.997	40.6± 5.8	50	6.9
6	502	1800	Zircon	4.24	(610)	6.59	(474)	1.08	41.5± 1.8	6	180
7	328	1345	---do--	4.09	(910)	8.32	(924)	1.28	37.6± 1.5	6	190
		1341	Apatite[2]	.108	(450)	.116	(485)	1.02	56.4± 7.4	100	3.3
8	430a	1322	Zircon	3.62	(787)	5.41	(589)	1.04	41.5± 1.8	6	150
		1306	Apatite	.115	(479)	.160	(667)	1.00	42.8± 5.1	100	4.6
9	420	2337	Zircon	4.75	(1122)	8.80	(1039)	1.13	36.4± 1.9	6	220
10	W-1-75	1320	---do--	6.35	(912)	7.16	(514)	1.05	55.5± 2.7	6	200
		1304	Apatite	.149	(275)	.136	(251)	1.02	66.5±11.6	100	3.8
11	150	590	Zircon	8.12	(1240)	10.38	(793)	1.17	54.7± 4.8	6	280
		591	Apatite	.162	(337)	.164	(342)	1.13	66.4±12.	50	4.7
12	444	1323	Zircon	10.30	(1045)	9.82	(500)	1.03	64.1± 3.7	4	270
		1307	Apatite	.102	(427)	.102	(425)	.990	59.3± 8.1	100	3.0
13	325	1321	Zircon	5.12	(1208)	5.25	(620)	1.05	60.9± 3.2	6	140
		1305	Apatite	.110	(457)	.104	(434)	1.01	63.3± 8.5	100	3.0

[1] Numbers in parentheses show total number of tracks counted in each determination.
[2] Sample has many defects.

TABLE 9.—*New chemical analyses and norms of Tertiary igneous rocks from South Park-Breckenridge region*

[Major oxides determined by Hezekiah Smith, U.S. Geological Survey, 1976, using rapid methods described by Shapiro (1975, p. 43–45). Minor elements determined by semiquantitative spectrographic methods by Leung Mei, U.S. Geological Survey, 1976. CIPW norms calculated on the basis of major-oxide analyses recalculated to 100 percent after deduction of volatiles. The standard deviation of any single answer should be taken as plus 50 percent and minus 33 percent. Looked for but not found: Ag, As, Au, Bi, Cd, Dy, Er, Gd, Ge, Hf, Ho, In, Ir, Li, Lu, Mo, Os, Pd, Pr, Pt, Re, Rh, Ru, Sb, Sm, Sn, Ta, Tb, Th, Tl, Tm, U, W]

	Paleocene volcanic rocks					Eocene and Oligocene			
						Intrusive rocks		Volcanic rocks	
Field No.	323	325	444	150	W-1-75	222	328	421	430A
Lab No.	W-191534	W-191538	W-191539	W-191533	W-191540	W-191535	W-191536	W-191541	W-191542
Major oxides (percent)									
SiO_2	55.9	62.9	66.3	67.0	67.8	58.1	63.3	66.3	69.6
Al_2O_3	16.7	15.6	15.5	14.6	16.1	16.4	16.7	15.5	15.1
Fe_2O_3	3.9	2.1	3.4	1.7	1.7	3.6	3.1	1.9	2.0
FeO	3.2	3.2	1.6	1.4	.88	4.0	1.2	2.3	1.1
MgO	3.4	1.9	1.5	1.6	.96	3.3	1.4	1.0	.72
CaO	5.4	4.6	3.8	4.5	4.5	5.8	3.5	3.4	3.1
Na_2O	3.5	4.1	2.8	2.4	2.8	3.2	3.5	3.4	3.1
K_2O	2.1	2.8	1.3	1.9	1.7	3.2	4.7	3.9	3.4
H_2O^+	3.1	.80	2.0	2.8	2.1	.94	.77	.80	.79
H_2O^-	1.9	.40	2.4	1.5	1.1	.12	.78	.49	.28
TiO_2	.74	.59	.39	.47	.35	.99	.72	.79	.48
P_2O_5	.40	.34	.18	.33	.16	.48	.32	.36	.20
MnO	.08	.14	.06	.08	.05	.12	.07	.05	.04
CO_2	.08	.01	.02	.01	.03	.05	.03	.01	.02
F	.04	.04	.02	.04	.01	.07	.08	.10	.05
Sum	100	100	101	100	100	100	100	100	100
Major oxides recalculated to 100 percent after deduction of volatiles (percent)									
SiO_2	58.61	64.01	68.47	69.61	69.90	58.57	64.26	66.97	70.27
Al_2O_3	17.51	15.87	16.01	15.21	16.60	16.53	16.95	15.76	15.35
Fe_2O_3	4.09	2.14	3.51	1.77	1.75	3.63	3.15	1.92	2.03
FeO	3.36	3.26	1.65	1.46	.91	4.03	1.22	2.32	1.12
MgO	3.56	1.93	1.55	1.67	.99	3.33	1.42	1.01	.73
CaO	5.66	4.68	3.92	4.69	4.64	5.85	3.55	3.43	3.15
Na_2O	3.67	4.17	2.89	2.50	2.89	3.23	3.55	3.43	3.15
K_2O	2.20	2.85	1.34	1.98	1.75	3.23	4.77	3.94	3.46
TiO_2	.78	.60	.40	.49	.36	1.00	.73	.80	.49
P_2O_5	.42	.35	.19	.34	.16	.48	.32	.36	.28
MnO	.15	.14	.06	.08	.05	.12	.07	.05	.04

TABLE 9.—*New chemical analyses and norms of Tertiary igneous rocks from South Park-Breckenridge region*—Continued

	Paleocene volcanic rocks					Eocene and Oligocene Intrusive rocks		Eocene and Oligocene Volcanic rocks	
Field No.---	323	325	444	150	W-1-75	222	328	421	430A
Lab No.-----	W-191534	W-191538	W-191539	W-191533	W-191540	W-191535	W-191536	W-191541	W-191542
CIPW Norms									
Q----------	11.89	16.35	36.32	35.87	35.44	11.01	16.52	23.42	31.43
C----------	---	---	3.11	1.25	1.91	---	.26	.47	1.18
Or---------	13.01	16.84	7.93	11.70	10.36	19.06	28.19	23.28	20.43
Ab---------	31.05	35.30	24.47	21.16	24.43	27.30	30.06	29.06	26.67
An---------	24.80	16.17	18.25	21.01	21.94	21.11	15.50	14.66	14.31
Hy-en-------	8.71	3.70	3.86	4.15	2.46	6.94	3.54	2.52	1.82
Hy-fs-------	1.74	2.68	---	.56	---	2.50	---	1.46	---
Di-Wo-------	.23	2.00	---	---	---	1.98	---	---	---
Di-en-------	.17	1.11	---	---	---	1.34	---	---	---
Di-fs-------	.03	.81	---	---	---	.48	---	---	---
Mt---------	5.93	3.10	4.36	2.57	2.05	5.26	2.04	2.78	2.32
Hm---------	---	---	.50	---	.34	---	1.74	---	.43
Il---------	1.47	1.14	.76	.93	.69	1.98	1.39	1.52	.93
Ap---------	.99	.82	.44	.81	.39	1.15	.77	.86	.48
Minor elements (parts per million)									
B----------	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<5.2	<4.4
Ba---------	900	1100	970	1100	910	1200	1600	1100	1200
Be---------	.98	1.3	1.2	1.4	1.3	1.9	2.9	2.9	2.2
Ce---------	<130	130	75	88	95	150	210	180	200
Co---------	14	12	5.7	6.0	5.8	18	8.7	11	7.1
Cr---------	17	57	6.9	6.9	7.5	46	6.9	19	5.6
Cu---------	20	17	5.7	6.4	11	18	11	26	5.9
Eu---------	2.6	2.2	<2.1	<2.5	2.4	3.0	3.8	3.3	2.8
Ga---------	20	18	14	13	18	26	24	22	18
La---------	28	59	35	33	44	70	100	97	100
Mn---------	1100	1100	540	540	430	1300	750	520	420
Nb---------	<4.4	12	4.6	5.0	<4.4	9.8	19	17	7.2
Nd---------	<65	<65	<65	<65	<65	67	84	89	82
Ni---------	11	20	<6.5	<6.5	>6.5	21	8.4	10	<6.5
Pb---------	<14	14	15	<14	18	22	30	17	18
Sc---------	14	18	12	9.9	7.9	21	15	15	9.1
Sr---------	1200	940	1200	1100	1500	980	770	870	750
V----------	100	110	40	37	41	120	70	120	53
Y----------	15	25	13	26	12	20	25	29	16
Yb---------	2.5	3.3	2.3	3.1	1.3	3.4	4.7	3.8	2.1
Zn---------	87	50	39	49	36	98	38	56	44
Zr---------	93	220	120	200	120	110	490	220	170

Potassium-Argon and Fission-Track Zircon Ages of Cerro Toledo Rhyolite Tephra in the Jemez Mountains, New Mexico

By G. A. IZETT, J. D. OBRADOVICH, C. W. NAESER, *and* G. T. CEBULA

SHORTER CONTRIBUTIONS TO ISOTOPE RESEARCH
IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199-D

CONTENTS

ILLUSTRATIONS

TABLES

POTASSIUM-ARGON AND FISSION-TRACK ZIRCON AGES OF CERRO TOLEDO RHYOLITE TEPHRA IN THE JEMEZ MOUNTAINS, NEW MEXICO

By G. A. IZETT, J. D. OBRADOVICH, C. W. NAESER, and G. T. CEBULA

ABSTRACT

Pumice units of the Cerro Toledo Rhyolite of early Pleistocene age in Pueblo Canyon in the eastern part of the Jemez Mountains of north-central New Mexico lie stratigraphically between the Otowi (lower) and Tshirege (upper) Members of the Bandelier Tuff. The K-Ar ages of sanidine, plagioclase, and hornblende from a lower unit of air-fall pumice of the Cerro Toledo are 1.46±0.03 m.y., 1.50±0.03 m.y., and 1.58±0.11 m.y., respectively, based on the newly recommended decay constants for ^{40}K, A, K-Ar isochron age for the three minerals is 1.47±0.04 m.y. The K-Ar age of sanidine from the uppermost pumice unit of the Cerro Toledo is 1.23±0.02 m.y. These K-Ar ages are stratigraphically compatible with K-Ar ages of the lower and upper members of the Bandelier Tuff determined by G. B. Dalrymple in 1968. Zircon fission-track ages of the lower unit of the Cerro Toledo are 1.39±0.11 m.y. and 1.46±0.12 m.y. The isotopic ages here reported for the Cerro Toledo Rhyolite coupled with those determined by Dalrymple for the Bandelier Tuff provide the basis for dating their downwind tephra correlatives in the southern High Plains of Kansas, New Mexico, and Texas.

INTRODUCTION

At several localities in the southern High Plains (fig. 11, table 10), such as the Borchers Ranch locality (Hibbard, 1941) in Meade County, Kans., deposits of volcanic ash occur (9 m stratigraphically above the type B Pearlette ash) that have mineralogical and chemical affinities with tephra of early Pleistocene age in the Jemez Mountains, north-central New Mexico. Elsewhere in the southern High Plains of New Mexico and Texas (fig. 11), volcanic ash beds tentatively correlate with two large pyroclastic units, the Guaje and Tsankawi Pumice beds (of the Otowi and Tshirege Members, respectively, of the Bandelier Tuff) (Izett and others, 1972; G. A. Izett, unpub. data, 1968-1979); but until the present, downwind equivalents of the Cerro Toledo Rhyolite, which lies between these two units, have not been recognized. If, in the future, these deposits of volcanic ash can be correlated with certainty with their suspected source-area tephra units, then they will have the potential of increasing the stratigraphic resolving power of the established sequence of ash beds and increasing the stratigraphic usefulness of associated fossil land mammals. The usefulness of these potential marker volcanic-ash beds may be further enhanced if reliable K-Ar ages can be assigned to their source-area equivalents. It is the purpose of this report to present K-Ar ages of the Cerro Toledo Rhyolite tephra units, which previously have not been dated but whose stratigraphic position between the Otowi and Tshirege Members of the Bandelier Tuff is well established.

The samples chosen for K-Ar age determinations were collected from the eastern Jemez Mountains (fig. 12) in north-central New Mexico. Large samples (77G55 and 77G56) were taken from two air-fall pumice units (fig. 13) of the Cerro Toledo Rhyolite of early pleistocene age in Pueblo Canyon east of Los Alamos, N. Mex. Smith, Bailey, and Ross (1970) did not map the deposits of Cerro Toledo Rhyolite at the sample locality in Pueblo Canyon, owing to their small areal extent (R. L. Smith, oral commun., 1977). According to Smith (oral commun., 1977) and Smith, Bailey, and Ross (1970), the pumice units sampled are pyroclastics associated with the emplacement of rhyolite domes. These domes were emplaced following the eruption of the lower Bandelier Tuff (Otowi Member) of early Pleistocene age and the subsequent collapse that formed the Toledo caldera.

At the sample locality, the two units sampled are the uppermost of several discrete air-fall pumice beds interlayered with tuffaceous sediments that lie in

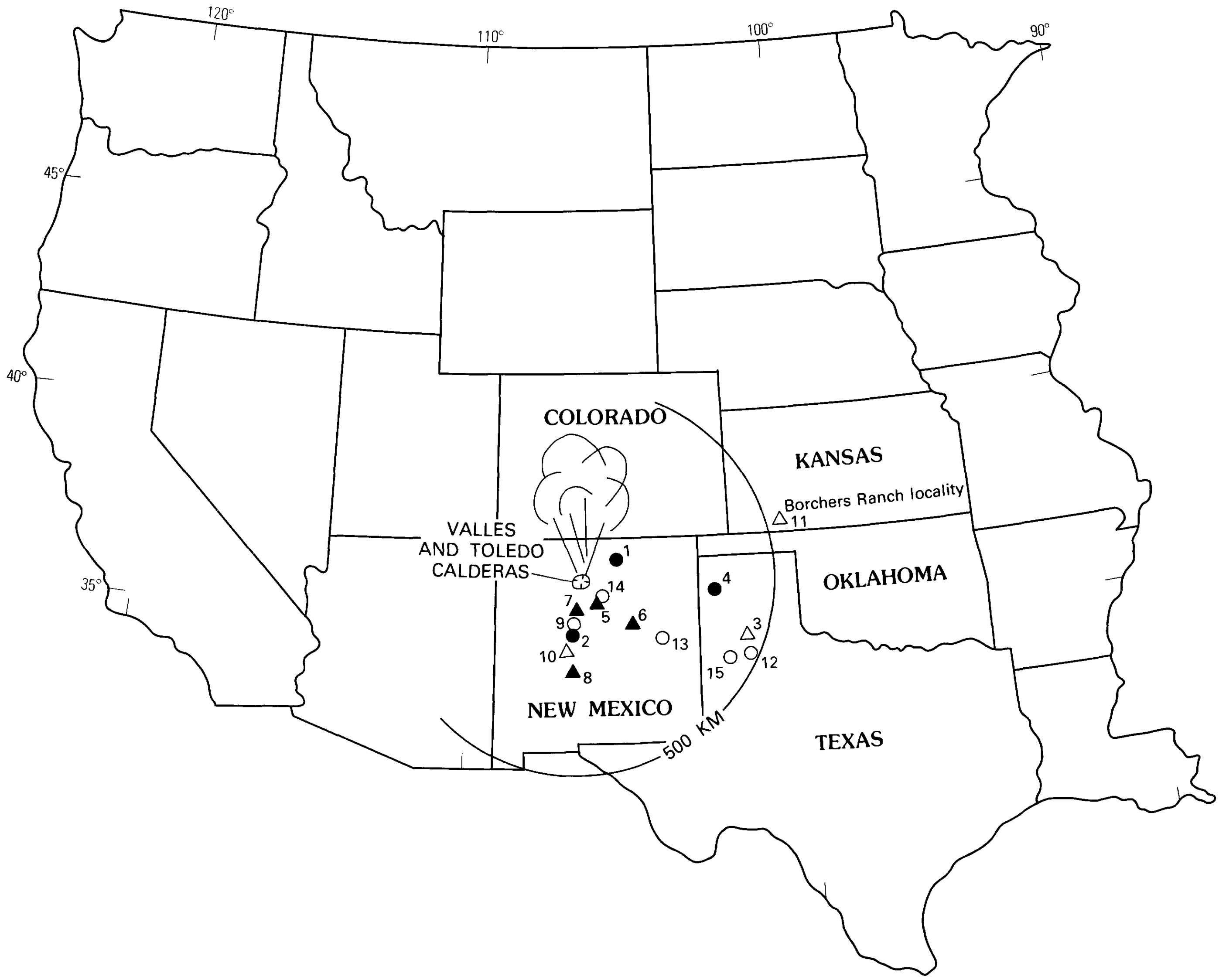


FIGURE 11.—Map of Western United States showing the distribution of lower Pleistocene volcanic-ash beds derived from pyroclastic eruptions from the Jemez Mountains area, New Mexico. Volcanic-ash-bed localities: Guaje ash, open circle; Cerro Toledo ash, filled triangle; Jemez Mountains-derived ash suspected to be Cerro Toledo ash, open triangle; and Tsankawi ash, filled circle. Correlation of volcanic-ash beds here provisionally assigned to the Cerro Toledo and Tsankawi ashes with their suspected source-data tephra is tentative until more mineralogical and chemical data are available. Localities are described in table 10.

stratigraphic succession above the Guaje Pumice bed and overlying ash flows of the Otowi Member and below the Tsankawi Pumice Bed and overlying ash flows of the Tshirege Member. Figure 12 shows the nomenclature for lower Pleistocene pyroclastic units of the Jemez Mountains, N. Mex. K-Ar sanidine ages of samples of the Bandelier Tuff were determined by G. B. Dalrymple and reported in a paper by Doell and others (1968, p. 238). Dalrymple's K-Ar sanidine ages are given in table 11, as well as those ages recalculated using the new decay constants recently recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1977).

METHODOLOGY

Mineral separations were made on the two samples from two of the air-fall pumice units of the Cerro Toledo Rhyolite by G. T. Cebula, M. G. Sawlan, and J. W. Groen of the U.S. Geological Survey. About 28 kg of sample 77G55 was used to obtain 39 g of calcic albite, 10 g of sanidine, and 0.04 g of zircon. About 2 kg of sample 77G55 was used to obtain about 10 g of

TABLE 10.—*Description of localities of Jemez Mountains-derived tephra deposits shown in figure 11.*

[Leaders (---) indicate data unavailable]

No.	Tephra bed	Approx. thickness (m)	Locality description	Collector	Sample Nos.
1.	Tsankawi--------	1	In Pleistocene deposits in roadcut along U.S. Highway 64 about 0.98 km southwest of junction with New Mexico State Highway 96, about 1.46 km southwest of the church at Ranchos de Taos in the Taos Southwest 7 1/2-minute minute quad., Taos County, N. Mex.	G. R. Scott-----	77W29
2.	---do-----------	1.5	In Pleistocene deposits near center of sec. 26, T. 7 N., R. 1 E., in Dalies 7 1/2-minute quad., Valencia County, N. Mex.	R. E. Wilcox----	66W69
3.	Cerro Toledo(?)-	1	About 2 m above base of 35-m-thick Pleistocene sequence (Tule Formation) along Rock Creek about 3 km north of Rock Creek Store in Cope Creek 7 1/2-minute quad., Briscoe County, Tex.	G. A. Izett-----	68G63, 75G11 75G32, 77G103, 77G104, 76G20
4.	Tsankawi(?)-----	3	West of Channing, Tex., east of Rita Blanca Creek in NE 1/4 sec. 18, block 49, above windmill marked with altitude 3,555 feet in Channing NW 7 1/2-minute quad., Hartley County, Tex. Sample 77G28 is from second tephra bed about 3 m higher, above intervening sandstone.	----do----------	77G27, 77G28
5.	Cerro Toledo----	1.2	Pumice lapilli bed in abandoned pumice pit in SE 1/4 NE 1/4 sec. 24, T. 16 N., R. 8 E., Turquoise Hill 7 1/2-minute quad., Santa Fe County, N. Mex.	R. E. Wilcox----	65W123
6.	---do-----------	---	Abandoned tephra pit about 13 km south of U.S. Highway 66 about 12.8 km west of junction with U.S. Highway 84, Guadalupe County, N. Mex.	R. H. Weber-----	66W162
7.	---do-----------	1.4	Pumice gravel bed about 4.8 km southeast of San Felipe Pueblo in NE 1/4 NE 1/4 sec. 33, T. 14 N., R. 5 E., San Felipe 7 1/2 minute quad., Santa Fe County, N. Mex.	R. E. Wilcox----	65W121
8.	---do-----------	4.5	Pumice gravel at southwest corner of sec. 26, T. 4 S., R. 1 E., San Antonio 15-minute quad., Socorro County, N. Mex.	R. H. Weber-----	66W156
9.	Guaje-----------	1.5	Ash and pumice lapilli bed in roadcut along Edith Blvd. near Albuquerque, N. Mex., NW 1/4 SE 1/4 SW 1/4 sec. 22, T. 11 N., R. E., Alameda 7 1/2-minute quad., Bernalillo County, N. Mex.	R. E. Wilcox, P. W. Lambert.	65W116
10.	Cerro Toledo(?)-	---	Pleistocene channel deposit at north edge of New Mexico Institute of Mining Technology at Socorro, N. Mex. Tephra deposits now destroyed.	R. H. Weber-----	66W160
11.	---do-----------	.1	About 9.1 m above Pearlette type B ash (Pliocene) in Pleistocene sediments in Borchers Ranch area, SE 1/4 sec. 16, T. 31 S., R. 28 W., Irish Flats NE 7 1/2-minute quad., Meade County, Kans. Ash bed incorrectly called type S Pearlette by some.	C. W. Hibbard--- G. A. Izett-----	73W28 74G42, 74G49, 74G51, 78G140
12.	Guaje-----------	.4	Roadcut along Texas State Highway 193 in NW 1/4 NE 1/4 sec. 1, block 3, of Eastland County school lands in Floydada SE 7 1/2-minute quad., Crosby County, Tex.	G. A. Izett-----	70G17
13.	---do-----------	.6	Roadcut along U.S. Highway 60 about 3.85 km west of Pecos River bridge in SE 1/4 NE 1/4 sec. 32, T. 3 N., R. 25 E., Fort Sumner 7 1/2-minute quad., DeBaca County, N. Mex.	---do-----------	74G30
14.	---do-----------	2	Pumice lapilli bed in Arroyo Hondo at south edge of Santa Fe 7 1/2-minute quad., Santa Fe County, N. Mex.	R. E. Wilcox---- G. A. Izett-----	65W124 75G3
15.	---do-----------	1	Roadcut of Farm Road 835 along south wall of Yellowhouse Canyon just north of junction with Farm Road 3020 in Buffalo Springs Lake 7 1/2-minute quad., Lubbock County, Tex.	G. A. Izett-----	75G28

TABLE 11.—*Reported and recalculated K-Ar ages of the Otowi and Tshirege Members of the Bandelier Tuff of north-central New Mexico*

Unit		Subunit	K-Ar age (m.y.) Reported by Doell and others (1968)[1]	K-Ar age (m.y.) Recalculated using new decay constants[2]
Bandelier Tuff	Tshirege Member	Ash flows	1.02±0.04 1.06±0.03	1.05±0.04 1.09±0.03
		Tsankawi Pumice Bed	1.09±0.03	1.12±0.03
	Otowi Member	Ash flows	1.48±0.09 1.44±0.04	1.52±0.09 1.48±0.04
		Guaje Pumice Bed	1.37±0.04	1.40±0.04

1 $^{40}K/K_{total}=1.19\times10^{-4}$; $\lambda_{\epsilon}=0.585\times10^{-10}yr^{-1}$; $\lambda_{\beta}=4.72\times10^{-10}yr^{-1}$.
2 $^{40}K/K_{total}=1.167\times10^{-4}$; $\lambda_{\epsilon}+\lambda_{\epsilon'}=0.581\times10^{-10}yr^{-1}$;
$\lambda_{\beta}=4.962\times10^{-10}yr^{-1}$ (Steiger and Jager, 1977).

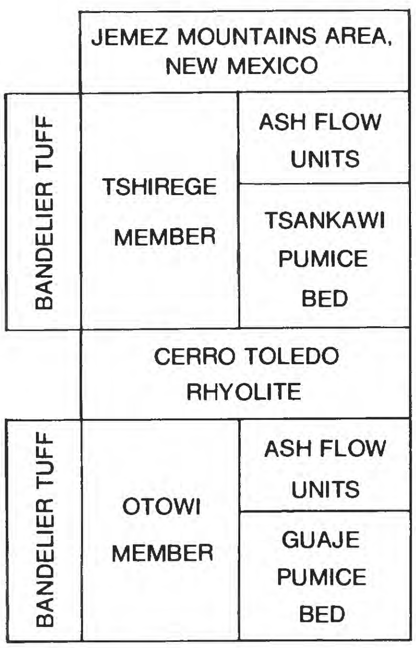


FIGURE 12.—Diagram showing the nomenclature of lower Pleistocene pyroclastic units of the Jemez Mountains area, north-central New Mexico. Modified from Smith, Bailey, and Ross (1970).

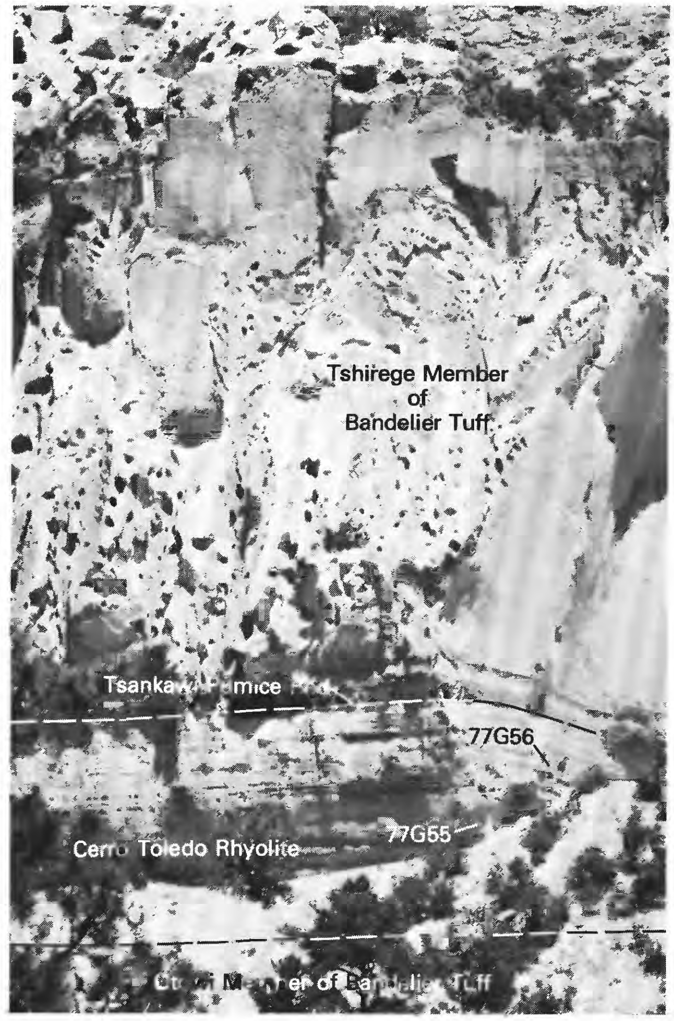


FIGURE 13.—View in Pueblo Canyon, NW¼NW¼ sec. 13, T. 6 E., R. 19 N., Guaje Mountain 7½-minute quadrangle, Los Alamos County, N. Mex., showing the stratigraphic succession where samples 77G55 and 77G56, used for K-Ar age determinations, were collected from the Cerro Toledo Rhyolite of early Pleistocene age. Topmost part (covered) of the lower Bandelier Tuff (Otowi Member) is in lower part of photograph; the Otowi Member is overlain by a succession of air-fall pumice units of the Cerro Toledo Rhyolite and the Tshirege Member of the Bandelier Tuff.

sanidine. The separation procedure for sample 77G55 consisted of screening the raw sample with a 4.75-mm (4-mesh) sieve and collecting only those 4.75-mm or larger pumice lumps that floated in water. Only the water-floatable pumice lumps were used for the mineral separations to insure that non-pumiceous accidental lithic fragments would not contribute material to the mineral separations. The pumice lumps were ultrasonically scrubbed, dried at about 50°C, and crushed and pulverized so that the sample would pass through a 300-µm (50-mesh) sieve. About 2 kg of sample was lost during sample preparation. Plagioclase was recovered using a bromoform and acetone mixture cut to appropriate specific gravity from the 300-t0 100-µm size range (-50 to +150 mesh), whereas the hornblende, sanidine, and zircon were recovered from the less-than-300-µm (-50 mesh) size range owing to their small size and scarcity. The purity of the mineral separates was improved by using a magnetic separator set at appropriate current, forward tilt, and side tilt. Sanidine was recovered from sample 77G56 using the same procedures as for 77G55. Because many of the mineral grains had glass welded to their edges, the mineral grains were etched with hydrofluoric acid (24 percent) to remove the glass, using the following etch times:

77G56	sanidine	2 minutes
77G55	sanidine	3 minutes
77G55	plagioclase	3 minutes
77G55	hornblende	6 minutes

Following the hydrofluoric acid etch, the minerals were ultrasonically scrubbed for about 5 minutes and sized as follows:

sanidine (77G56)	300 to 106µm (-50 to +140 mesh)
sanidine (77G55)	300 to 100 µm (-50 to +150 mesh)
plagioclase (77G55)	300 to 106 µm (-50 to +140 mesh)
hornblende (77G55)	=300 µm (-50 mesh)

After the samples were sized, they were split, using a Jones-type microsplitter[1], into fractions for argon and potassium analysis. Argon was collected and argon isotopic ratio determined from melted splits of the samples.

The potassium content of splits of the minerals used for argon analysis was determined by three methods—isotope dilution, flame photometry, and electron microprobe (table 12), although only the potassium contents as determined by isotope dilution were used to calculate the ages. Isotope dilution analysis of the samples was done by J. D. Obradovich and Kiyoto Futa on all samples. Flame photometry was done by G. A. Izett and Wayne Montjoy to compare the results (table 12) with those done by isotope dilution.

The potassium content of the samples was determined by G. A. Izett using an Applied Research Laboratories EMX model electron microprobe to compare the results by this method with the isotope dilution results. Splits of the samples were mounted in epoxy in holes drilled in an aluminum wafer. The potassium content was determined by analyzing the specimens using 15 kilovolts operating voltage and 15 nanoamperes sample current measured on benitoite. A fixed count of beam current was used with a counting period of about 15 seconds. The analytical procedure consisted of analyzing 10 grains of each of four standard feldspar samples. A computer program linked to the electron microprobe (1) calculated a mean value of the number of counts and its associated standard deviation for potassium in the standard feldspars and (2) determined a least-squares curve relating the number of counts to weight percent potassium. Ten grains of each of the samples of unknown potassium content were analyzed, and their mean counts were compared by the computer with the curve relating counts to weight percent of the standard feldspars. The potassium contents determined in this way for the different runs were averaged to give the potassium content of each sample, and the results are in fairly good agreement with the results from isotope diluton (table 12).

DISCUSSION

The K-Ar age determinations (table 12) made on pumice units of the Cerro Toledo Rhyolite of Pleistocene age are compatible, within their analytical uncertainty, with K-Ar ages of underlying and overlying units of the Bandelier Tuff determined by G. B. Dalrymple (reported in Doell and others, 1968; and table 10). The results suggest that the lower pumice unit of the Cerro Toledo, herein dated 1.47±0.04 m.y. (77G55), is very close in age to the Otowi Member of the Bandelier Tuff as determined by G. B. Dalrymple (1.45 m.y.; average of 3 determinations (weighted mean)) and cannot be separated from it based on the K-Ar age determinations at hand. The uppermost pumice unit of the Cerro Toledo Rhyolite (77G56) has a K-Ar age (1.23+0.02 m.y.) significantly younger

[1]Use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

TABLE 12.—*K-Ar ages of minerals from pumice units of the Cerro Toledo Rhyolite, Jemez Mountains, New Mexico*

Sample	Mineral	Lab No. DKA-	K_2O (percent) (1)	(2)	(3)	Sample weight (g)	Moles radiogenic ^{40}Ar	Percent radiogenic ^{40}Ar	K-Ar age[4] (m.y.)
77G56	Sanidine----	3502	7.21	7.33	7.22	3.9867	5.11×10^{-11}	56.8	1.23±0.02
77G55	---do-------	3500	8.36	8.62	----	1.0727	1.89×10^{-11}	24.5	1.46±0.03
77G55	Plagioclase-	3499	1.98	2.01	1.98	12.5853	5.36×10^{-11}	28.3	1.50±0.03
77G55	Hornblende--	3497	.56	.56	----	4.2865	5.50×10^{-12}	6.1	1.58±0.11

[1]Potassium determined by J. D. Obradovich and K. Futa by the isotope dilution technique.
[2]Potassium determined by G. A. Izett using the electron microprobe.
[3]Potassium determined by G. A. Izett and W. Mountjoy by flame photometry technique.
[4]Decay constants: $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $\lambda_\varepsilon + \lambda_{\varepsilon'} = 0.581 \times 10^{-10}$ yr^{-1}. ^{40}K abundance: $^{40}K = 1.167 \times 10^{-4}$ atom/atom K. Precision of age determinations given at the 1-sigma level. K-Ar ages calculated using the potassium content as determined by isotope dilution.

TABLE 13.—*Zircon fission-track age determination for sample 77G55, from an airfall pumice unit of the Cerro Toledo Rhyolite, Jemez Mountains, New Mexico*

[$\beta_f = 7.03 \times 10^{-17} yr^{-1}$]

Lab No. DF-	Spontaneous-track density[1] (ρ_s) (10^6 tracks/cm^2)	Induced-track density[1] (ρ_i) (10^6 tracks/cm^2)	Neutron flux (ϕ)($10^{15} n/cm^2$)	Fission-track age[2] (m.y.)	U (ppm)
1646	0.423 (45)	19.14 (1019)	1.05	1.39±0.11	520
1646A	.374 (71)	7.55 (717)	.493	1.46±0.12	440

[1]Total number of tracks counted shown in parentheses.
[2]Error is ±2 sigma.

than the K-Ar age of the underlying pumice unit (77G55) of the Cerro Toledo (1.47±0.04 m.y.), and significantly older than K-Ar ages of the overlying Tshirege Member of the Bandelier Tuff as dated by G. B. Dalrymple (about 1.09 m.y.; average of 3 determinations (weighted mean)).

The K-Ar ages of sanidine (1.46±0.03 m.y.), plagioclase (1.50+0.03 m.y.), and hornblende (1.58±0.11 m.y.) of sample 77G55 are in agreement with each other within their analytical uncertainty at the 2-σ level. Because of the small amount of hornblende recovered through mineral separations from the phenocryst-poor rhyolite (77G55), and because of the low potassium content of the hornblende, the K-Ar age of the hornblende has a fairly high uncertainty. A K-Ar isochron plot of the analytical data for the three minerals from sample 77G55 is shown in figure 14, and the age calculated from the data is 1.47±0.04 m.y. The analytical precision estimate for this isochron age was calculated using a modified York linear regression. The minerals contain no analytically significant amount of inherited argon, inasmuch as the $^{40}Ar/^{36}Ar$ intercept is about 297.

Two fission-track age determinations (table 13) were made by C. W. Naeser on zircon separated from sample 77G55 of the Cerro Toledo. The calculated ages are 1.39±0.11 m.y. and 1.46±0.12 m.y. (2σ), and these ages are concordant with the K-Ar ages within their analytical uncertainty. The fission-track age of

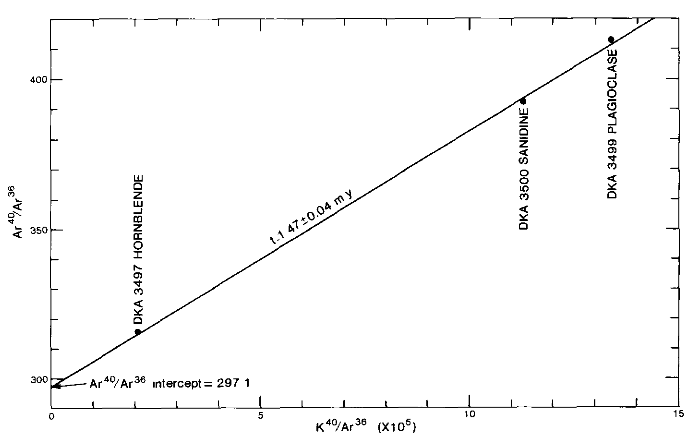


FIGURE 14.—K-Ar isochron plot for three minerals from sample 77G55 of a pumice unit in Cerro Toledo Rhyolite in the eastern Jemez Mountains, N. Mex.

1.46 m.y. is perhaps the better of the two, inasmuch as it was made following re-irradiation of the original sample, which had too high an induced-track density for optimum counting conditions.

REFERENCES CITED

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico, *in* Studies in volcanology—A memoir in honor of Howel Williams: Geological Society of America Memoir 116, p. 211-248.

Hibbard, C. W., 1941, The Borchers fauna, a new Pleistocene interglacial fauna from Meade County, Kansas: University of Kansas Science Bulletin 38, pt. 7, p. 197-220.

Izett, G. A., Wilcox, R. E., and Borchardt, G. A., 1972, Correlation of a volcanic ash bed in Pleistocene deposits near Mount Blanco, Texas, with the Guaje Pumice bed of the Jemez Mountains, New Mexico: Quaternary Research, v. 2, no. 4, p. 554-578.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Investigations Map I-571, scale 1:250,000.

Steiger, R. H., and Jäger, E., 1977, Subcommission on Geochronology: Earth and Planetary Science Letters, v. 36, p. 359-362.

Fission-Track Dating of the Climax and Gold Meadows Stocks, Nye County, Nevada

By C. W. NAESER *and* FLORIAN MALDONADO

SHORTER CONTRIBUTIONS TO ISOTOPE RESEARCH
IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1199-E

CONTENTS

TABLES

FISSION-TRACK DATING OF THE CLIMAX AND GOLD MEADOWS STOCKS, NYE COUNTY, NEVADA

C. W. NAESER and FLORIAN MALDONADO

ABSTRACT

Fission-track ages indicate an age of 101 million years for the Climax stock and a minimum age of 93.6 million years for the Gold Meadows stock, both at the Nevada Test Site, Nye County, Nevada. Younger fission-track ages for some of the apatite concentrates suggest that the stocks have been within 4 kilometers of the surface since late Paleocene time.

RESULTS AND INTERPRETATION

The Climax stock, Nye County, Nevada (Maldonado, 1977), has been sampled in five locations for fission-track dating. Apatite from five of the samples was dated, as were zircon from two and sphene from one. A sample of the Gold Meadows stock, Nye County, Nevada, was also dated using apatite and zircon. The purpose of this study was to determine the thermal history of the respective stocks. Because apatite records the rock's most recent cooling regime (Naeser and Forbes, 1976), it is a very useful indicator of tectonic history.

Four of the five samples collected from the Climax stock (Maldonado, 1977) are outcrop samples (tables 14 and 15, Nos. 2-5). The fifth sample (table 14, No.1) is a drill core from a depth of 536 m in drill hole U15BGZ. Apatite from the four surface samples gave concordant fission-track ages, with an average of 101 ± 3.2 m.y. (± one standard error (σ) of the mean). This age is in excellent agreement with the stock's sphene and zircon ages, which give an average of 101±1.2 m.y. However, the apatite from the drill core gave a discordant age, 78.6±3.4 m.y.

The concordance of the fission-track ages of the surface samples means that the rock now exposed at the surface has never been above 100°C in the last 100 m.y.; these concordant ages also indicate the probable time of emplacement of the stock. Assuming that the geothermal gradient for this area was the same during the late Cretaceous as it presently is, about 25°C/km (Roy and others, 1968), we can state that this stock was intruded at a depth of less than 4 km. The discordant age of the drill-core apatite points to a somewhat different thermal history for the buried parts of the stock. There are two possible interpretations: The first is that the stock was emplaced at such a depth in the crust that the 100°C isotherm was between the rock presently at the surface and the rock at a depth of 500 m. This placement would have permitted the "surface" samples to cool to less than 100°C while the lower samples remained above 100°C for an extended time. The second interpretation is that the accumulation of sedimentary or volcanic materials buried the stock to such a depth that partial annealing of the apatite took place at some time after intrusion. It is not possible to distinguish between these two possibilities using the present data. If it is assumed that sample 1 (core) cooled through the 100°C isotherm 79 m.y. ago, an average uplift rate of 0.05 mm/yr can be calculated. Most of that uplift would have taken place prior to the deposition of the Belted Range Tuff on the Climax stock 13 m.y. ago.

The Gold Meadows stock, Nye County, Nevada (Snyder, 1977), was sampled at one surface site (tables 1 and 2, no. 6). The apatite and zircon from this sample have discordant fission-track ages: 55.6±2.8 m.y. and 93.6±4.3 m.y., respectively. These ages suggest a slightly more complex history for this stock than for the Climax stock. Apparently the Gold Meadows stock either was emplaced at a deeper level in the crust or was, at some later time, buried to a

TABLE 14.—*Fission-track data for samples from the Climax and Gold Meadows stocks, Nye County, Nevada*

[Decay constant λ_f=7.03×$10^{-17}$$yr^{-1}$]

Sample No.	Analysis No.	Mineral	Spontaneous-track density[1] (ρ_s) (10^6 tracks/cm^2)	Induced-track density[1] (ρ_i) (10^6 tracks/cm^2)	Neutron flux (Ø) (10^{15} n/cm^2)	Fission-track age (m.y.) ±2σ	Uranium content (ppm)
			Climax stock				
1	DF-1637	Apatite	0.287 (1195)	0.243 (1013)	1.12	78.6± 6.7	6.3
1	DF-1638	Sphene	19.79 (733)	43.84 (812)	3.87	104 ±11	330
1	DF-1639	Zircon	10.99 (1628)	7.21 (534)	1.12	101 ± 6.4	190
2	DF-1640	Apatite	.431 (1794)	.307 (1280)	1.12	93.3± 6.8	7.9
3	DF-1641	Apatite	.327 (1362)	.203 (845)	1.11	106 ± 9	5.3
4	DF-1642	Apatite	.372 (1552)	.248 (1032)	1.10	98.3± 7.9	6.5
5	DF-1645	Apatite	.349 (1454)	.212 (885)	1.10	107 ± 9	5.6
5	DF-1644	Zircon	17.36 (1366)	11.44 (450)	1.11	100 ± 6.4	300
			Gold Meadows stock				
6	DF-1646	Apatite	0.163 (681)	0.193 (803)	1.10	55.6± 5.6	5.0
7	DF-1647	Zircon	13.71 (1904)	9.58 (665)	1.10	93.6± 8.5	250

[1]Numbers in parentheses show total number of tracks counted in each determination.

TABLE 15.—*Sample localities in the Climax and Gold meadows stocks, Nye County, Nevada*

Sample No.	North latitude	West longitude	Site description	Quadrangle
		Granodiorite from Climax stock		
1	37°14'04"	116°03'27"	From drill hole U15bG2; 536m below collar.	Oak Spring
2	37°14'23"	116°03'16"	Surface outcrop	Do.
3	37°14'23"	116°03'50"	----do.-----	Do.
4	37°14'18"	116°03'54"	----do.-----	Do.
5	37°13'32"	116°03'40"	----do.-----	Do.
		Quartz monzonite from Gold Meadows stock		
6	37°13'52"	116°12'28"	Surface outcrop	Rainier Mesa

deeper level. It has a calculated uplift rate of about 0.07 mm/yr for the last 56 m.y. The zircon from the Gold meadows stock is apparently younger than the sphene and zircon from the Climax stock. This younger age could be the result of a deeper level of intrusion and (or) later burial of the Gold Meadows stock, or of the emplacement of the stock about 7 m.y. after the emplacement of the Climax stock.

OTHER AGES

Marvin and others (1970) reported six biotite K-Ar ages from the Climax stock and one from the Gold Meadows stock. The six biotite ages from the Climax stock range from 89 to 97 m.y. Using the IUGS constants for ^{40}K, we recalculated the ages, Obtaining 91 to 100 m.y. The oldest age is very close to the average fission-track age for the Climax stock. The 91.8-m.y. K-Ar biotite age for the Gold Meadows stock recalculates to 94.3 m.y., which is in very good agreement with the zircon age of 93.6 m.y.

ANALYTICAL METHODS

The apatites were dated by the population method (Naeser, 1976); they were etched in 7 percent HNO_3 for 25 seconds at room temperature. The zircon and sphene were dated by the external-detector method (Naeser, 1976). The zircon was etched in a KOH-NaOH eutectic melt (Gleadow and others, 1976), and the sphene, in 50 *M* NaOH at 140°C (Naeser, 1976).

ACKNOWLEDGMENTS

We wish to thank G. T. Cebula of the U.S. Geological Survey for his excellent mineral separations on these rocks.

REFERENCES CITED

Barnes, Harley, Houser, F. N. and Poole, F. G., 1963, Geologic map of the Oak Spring quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-214.

Gibbons, A. B. Hinrichs, E. N. Hansen, W. R., and Lemke, R. W., 1963, Geology of the Rainier Mesa quadrangle, Nye county, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-215.

Gleadow, A. J. W., Hurford, A. J., and Quaife, R. D., 1976, Fission-track dating of zircon—Improved etching techniques: Earth and Planetary Science Letters, v. 33, p. 273-276.

Maldonado, Florian, 1977, Summary of the geology and physical properties of the Climax stock, Nevada Test Site: U.S. Geological Survey Open-File Report 77-356, 27 p.

Marvin, R. F., Byers, F. M., Jr., Mehnert, H. H., Orkild, P. P., and Stern, T. W., 1970, Radiometric ages and stratigraphic sequence of volcanic and plutonic rocks, southern Nye and western Lincoln Counties, Nevada: Geological Survey of America Bulletin, v. 81, p. 2657-2676.

Naeser, C. W., 1976, Fission-track dating: U.S. Geological Survey Open-File Report 76-190, 68 p.

Naeser, C. W. and Forbes, R. B., 1976, Variation of fission-track ages with depth in two deep drill holes: EOS, American Geophysical Union Transactions, v. 57, p. 353.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, Francis, 1968, Heat flow in the United States: Journal of Geophysical Research, v. 73, p. 5207-5222.

Snyder, R. P., 1977, Geology of the Gold Meadows stock, Nevada Test Site: Available only from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as U.S. Geological Survey report USGS-474-179, 13 p.

☆ U S. GOVERNMENT PRINTING OFFICE: 1980—777-034/39