Reconnaissance Geology and Geochronology of the Precambrian of the Granite Mountains, Wyoming

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By ZELL E. PETERMAN *and* R. A. HILDRETH

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Radiometric dating establishes ages of 2,860 m.y. for an extensive metamorphic complex and 2,550 m.y. for a major granite batholith in the Granite Mountains

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CONTENTS

ILLUSTRATIONS

TABLES

RECONNAISSANCE GEOLOGY AND GEOCHRONOLOGY OF THE PRECAMBRIAN OF THE GRANITE MOUNTAINS, WYOMING

By Zell E. Peterman and R. A. Hildreth

ABSTRACT

The Precambrian of the western part of the Granite Mountains, Wyoming, contains a metamorphic complex of gneisses, schists, and amphibolites that were derived through amphibolite-grade metamorphism from a sedimentary-volcanic sequence perhaps similar to that exposed in the southeastern Wind River Mountains. Whole-rock Rb-Sr dating places the time of metamorphism at 2,860±80 million years. A high initial $^{87}Sr/^{86}Sr$ ratio of 0.7048 suggests that either the protoliths or the source terrane of the sedimentary component is several hundred million years older than the time of metamorphism. Following an interval of 300±100 million years for which the geologic record is lacking or still undeciphered, the metamorphic complex was intruded by a batholith and satellite bodies of medium- to coarse-grained, generally massive biotite granite and related pegmatite and aplite. The main body of granite is dated at 2,550±60 million years by the Rb-Sr method. Limited data suggest that diabase dikes were emplaced and nephrite veins were formed only shortly after intrusion of the granite.

Emplacement of the granite at about 2,550 million years ago appears to be related to a major period of regional granitic plutonism in the Precambrian of southern and western Wyoming. Granites, in the strict sense, that are dated between 2,450 and 2,600 million years occur in the Teton Range, the Sierra Madre, the Medicine Bow Mountains and the Laramie Range. This episode of granitic plutonism occured some 50 to 100 million years later than the major tonalitic to granitic plutonism in the Superior province of northern Minnesota and adjacent Ontario—the nearest exposed Precambrian W terrane that is analogous to the Wyoming province. Initial $^{87}Sr/^{86}Sr$ ratios of some of the Wyoming granites are higher than expected if the rocks had been derived from juvenile magmas and it is likely that older crustal rocks were involved to some degree in the generation of these granites.

Slightly to highly disturbed Rb-Sr and K-Ar mineral ages are obtained on rocks of the metamorphic complex and on the granite. These ages range from about 2,400 to 1,420 million years and are part of a regional pattern of lowered mineral ages of Precambrian W rocks of southern Wyoming. A major discontinuity in these mineral ages occurs along a line extending from the northern Laramie Range, through the northern part of the Granite Mountains, to the southeastern Wind River Mountains. North of this line, Rb-Sr and K-Ar biotite ages are 2,300 million years or greater, whereas to the south, the biotite ages decrease drastically over a short distance, to a common range of 1,600-1,400 million years. We suggest that these lowered ages represent regional cooling below the 300° C isotherm as a consequence of uplift and erosion of the large crustal block occurring south of the age discontinuity. In this interpretation, the westerly-trending age discontinuity would be a zone of major crustal dislocation that resulted from vertical tectonics in late Precambrian X or early Precambrian Y time.

INTRODUCTION

Precambrian igneous and metamorphic rocks are exposed in the Granite Mountains of central Wyoming—a block of Precambrian basement that was uplifted during the Laramide orogeny when vertical tectonics and thrust faulting resulted in the exposure of several major terranes of crystalline rock in Wyoming (fig. 1). The Granite Mountains uplift trends west-northwest and lies between the Wind River uplift on the west and the Laramie uplift on the east. The Phanerozoic and particularly the Cenozoic history of the Granite Mountains is complex, but a comprehensive account of this facet of the geology is given by Love (1970). Because of the economic importance of the Phanerozoic sedimentary rocks along the flanks and in basins adjacent to the Granite Mountains, geologic studies have emphasized these younger rocks. A few gold and sulfide occurences in Precambrian rocks were prospected and some were mined to a limited extent, but these did not prove sufficiently substantial to sustain operations. Nephrite (jade) occurs in Precambrian vein deposits and in Eocene conglomerates and Holocene alluvium derived therefrom; these deposits are important in a local gemstone trade.

Love (1970) reviewed the investigations of Precambrian rocks that had been made prior to 1965. Sherer (1969), in his study of nephrite deposits of central Wyoming, completed a

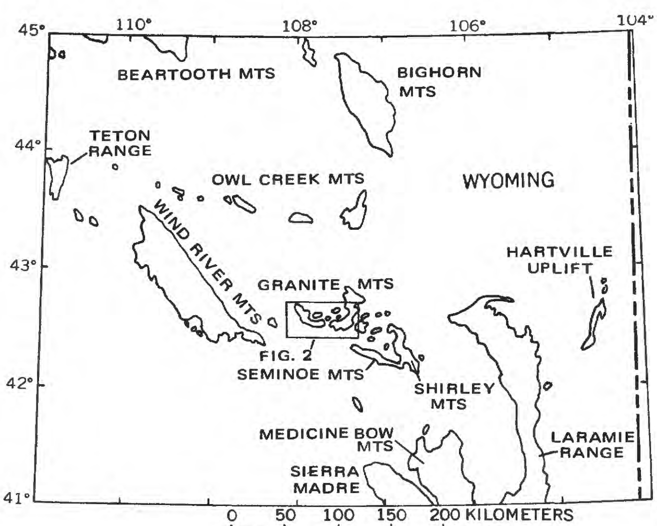


FIGURE 1.—Areas of exposed Precambrian in the Wyoming area (King and Beikman, 1974).

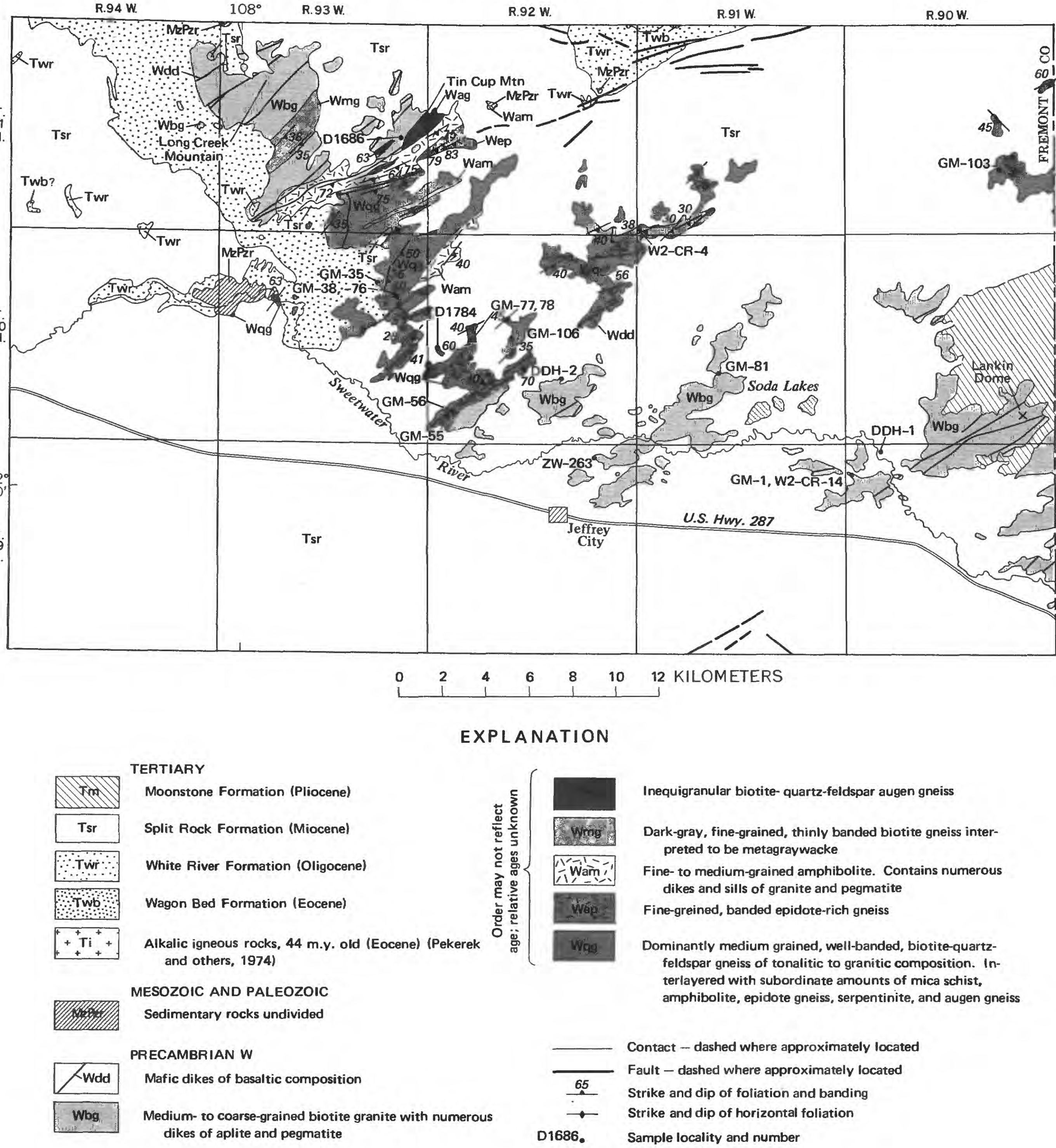
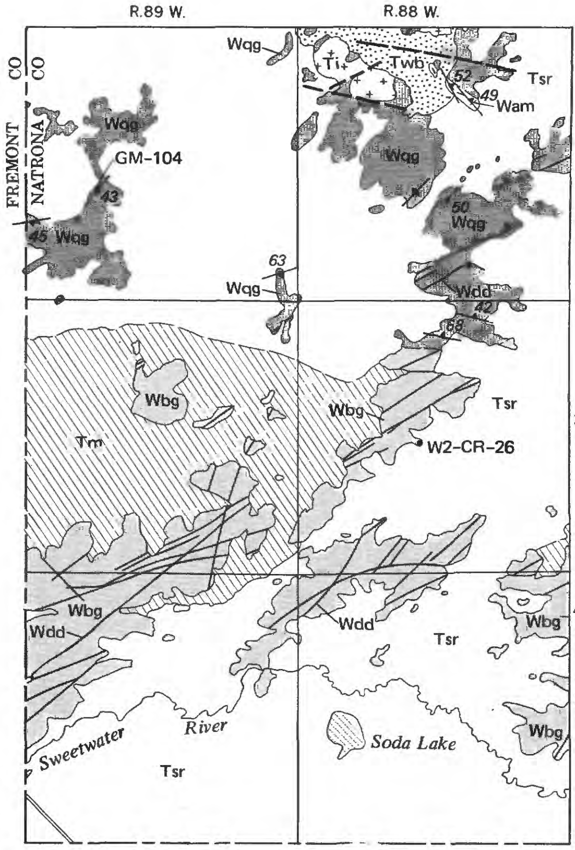


FIGURE 2.—Reconnaissance geology of the Precambrian of the western part of the Granite Mountains. Base and Phanerozoic geology from Love (1970, pl. 1). Sample numbers abbreviated for clarity.

detailed map of a small area of Precambrian gneisses in the western part of the Granite Mountains. Houston (1974) prepared reconnaissance maps of the Precambrian from several types of remote-sensing data. Stuckless and others (1977) have completed a preliminary geochemical and petrologic study of the granite in the Granite Mountains. The present study emphasizes the regional geology and geochronology of the Precambrian rocks of the western part of the Granite Mountains. We completed reconnaissance mapping in the summers of 1968 and 1969 and collected



samples for the geochronological study at that time.

Preliminary results of our geochronology study were previously summarized (Peterman and others, 1971). Other isotopic studies have emphasized the U-Th-Pb systematics in the granite and the metamorphic rocks. Rosholt and Bartel (1969) demonstrated that a large fraction of the uranium in the granite had been removed in relatively recent geologic time, the last 100 m.y. (million years), and suggested that the granite may have been a source for much or all of the uranium that forms the important economic deposits in adjacent Tertiary sandstones. Further work on the granite (Rosholt and others, 1973) and on gneisses of the metamorphic complex (NKomo and Rosholt, 1972) reinforced these earlier conclusions. This hypothesis conflicts with that of Love (1970) who, on the basis of geologic and geochemical data, concluded that the uranium in the Tertiary sandstones was probably derived by leaching of lacustrine tuff beds of the Pliocene Moonstone Formation.

We are especially grateful to Robert G. Coleman who introduced the senior author to the geology of the Granite Mountains, encouraged the study, and provided several samples for isotopic analyses. John Stacey assisted in the field work in the summer of 1968. The late William T. Henderson completed most of the chemical work attendant with the Rb and Sr analyses. G. T. Cebula and Jack Groen prepared all of the whole-rock and mineral samples. M. A. Lanphere and G.B. Dalrymple determined the $^{39}Ar/^{40}Ar$ ages and R. F. Marvin and H. H. Mehnert provided the conventional K-Ar ages. T. W. Stern analyzed zircon from the granite at Tincup Mountain. John Stuckless provided core samples from U.S. Geological Survey drill hole GM-1. J. David Love, Robert Houston, and John Stuckless provided many valuable comments on the manuscript. To all of these people, we express our sincere appreciation.

REGIONAL PRECAMBRIAN GEOLOGY

The Precambrian geology of the western part of the Granite Mountains (Tps. 29-31 N., Rs. 88-94 W.) is shown in figure 2. Three major terranes or lithologies are readily differentiated: (1) An assemblage of amphibolite-grade metamorphic rocks crops out in the northwestern and northern part of the area. (2) Granitic rocks, whence the name Granite Mountains, are part of a large batholith extending eastward beyond the map area. (3) Diabase dikes with dominant northeasterly trends intrude both the granitic and metamorphic rocks. The geologic maps prepared by Houston (1974) from various remote-sensing data and the reconnaissance mapping completed for this study are in excellent agreement.

METAMORPHIC COMPLEX

The metamorphic complex contains the oldest Precambrian rocks of the area and consists of a variety of schists and gneisses that attained amphibolite grade but locally have been retrograded. Foliation and compositional banding in this terrane trend northeasterly to easterly, and dips are generally in a southerly direction towards the granite. The metamorphic complex is divided into five major units based upon the dominant lithology in each (fig. 2): quartzofeldspathic gneiss; epidote-rich gneiss; amphibolite; biotite gneiss (interpreted to be metagraywacke); and augen gneiss. More detailed mapping would undoubtedly result in the recognition of a greater number of units. The relative ages of most of the metamorphic rocks are unknown. Some amphibolite and granitic gneiss are clearly intrusive but have been involved in the major period of folding and metamorphism. The major emphasis on the metamorphic rocks in the present study was on those cropping out in Tps. 30 and 31 N., Rs. 92 and 93 W. Other areas were examined in less detail and to the extent necessary to identify the major lithologic types present. Little effort was devoted to the metamorphic rocks cropping out in T. 31 N., R. 88 W., and the mapping of Carey (1959) was used for the northern part of this township. A photogeologic map of the central part of the township was prepared by Houston (1974), and his ground check identified an occurrence of Precambrian iron-formation, a unit not encountered elsewhere in the area. It is noteworthy that Love (1970) reported the presence of fragments of banded iron-formation in the Eocene Wagon Bed Formation (T. 32 N., R. 86 W.) and suggested that Precambrian and Paleozoic rocks to the south and southwest should be examined as potential sources for these

TABLE 1.—*Descriptions and modal analyses of metamorphic rocks*

[Asterisk by sample number indicates modal analysis by point counting (500-600 points). Other modes are visual estimates. Sample localities illustrated in figure 2]

Sample	Locality	Description
*GM-35-68	42°35′21″ N. 107°55′37″ W.	Light-gray, fine- to medium-grained, xenoblastic, inequigranular granodioritic gneiss. Leucocratic bands from 2 to 10 mm wide alternate with more biotite-rich bands from 1 to 10 mm wide. Plagioclase (An_{24}, 46 percent) is moderately sericitized. Microcline (11 percent) is fresh and occurs mainly as grains interstitial to plagioclase and quartz (34 percent), although a few larger porphyroblasts of microcline as much as 10 mm occur in the leucocratic bands. Epidote (1.1 percent) occurs as discrete subhedral grains in association with biotite (7.0 percent). Zircon, apatite, hornblende, altered allanite, and opaques are minor constituents.
*GM-38-68	42°35′04″ N. 107°54′55″ W.	Medium-gray, fine- to medium-grained, xenoblastic, inequigranular tonalitic gneiss. Alternating light and dark bands range from a few millimeters to several centimeters in thickness. Plagioclase (An_{27}, 52 percent) is only slightly altered to sericite—notably less so than in GM-35-68. Quartz (37 percent) locally forms composite ameboid lenses in the plane of foliation. A few grain boundaries show suturing. Biotite (8.1 percent) is completely unaltered and associated with epidote (1.0 percent) and trace amounts of allanite. Apatite, zircon, hornblende, and opaques are common accessory minerals.
*GM-76-68	42°35′04″ N. 107°54′55″ W.	Medium-gray, medium-grained, xenoblastic, inequigranular tonalitic gneiss. Banding is less distinctly developed than in sample GM-38-68 from the same locality. Composite grains of quartz (36 percent) and plagioclase (An_{27}, 51 percent) occur as eyes and discontinuous layers in the more biotite (10 percent) rich portions of the rock. Microcline (0.2 percent) occurs only as patch antiperthite in plagioclase. Plagioclase is somewhat saussuritized and biotite is locally partially chloritized and associated with epidote (1.2 percent). A few discrete grains of muscovite (1.7 percent) occur. Sphene, zircon, apatite, and opaques are accessory minerals.
*GM-77-68	42°33′58″ N. 107°52′18″ W.	Dark-gray, fine- to medium-grained, xenoblastic, inequigranular granodioritic gneiss with thin discontinuous leucocratic layers (as much as 5 mm) alternating with thicker (1 to several cm) mafic layers. Quartz (36 percent) occurs as both equant grains and as composite lenses elongated in the foliation plane defined by biotite (15 percent). Plagioclase (An_{25}, 29 percent) is only slightly sericitized. Microcline (12 percent) occurs both as discrete grains and as patches in plagioclase. Blue-green hornblende (5.6 percent) is concentrated in the mafic layers. Epidote (1.8 percent), euhedral sphene (0.5 percent), and opaques (0.2 percent) are abundant trace minerals. Apatite, zircon, and allanite are present.
*GM-78-68	42°33′58″ N. 107°52′18″ W.	Light-gray, fine-grained, xenoblastic, inequigranular granitic gneiss with thin (1-2-mm) and continuous leucocratic layers imparting a distinct fine-scale banding. Plagioclase (An_{22}, 30 percent) is only slightly altered to sericite. Microcline (30 percent) is a major constituent and locally is poikiloblastic with inclusions of quartz and plagioclase. Quartz (32 percent) locally occurs as composite lenses elongated in the extremely well developed foliation defined by the biotite (8.1 percent). Epidote, zircon, apatite, opaques, and chlorite are present in trace amounts.
*GM-98-68	42°32′38″ N. 107°12′40″ W.	Medium-gray, medium-grained, xenoblastic, inequigranular tonalitic gneiss. The rock has a well-developed foliation but is not banded. Plagioclase (An_{27}, 39 percent) is only slightly sericitized and biotite (6.7 percent) is locally chloritized. Only trace amounts of microcline occur (0.2 percent). Quartz (39 percent) occurs in places as very elongate lenses as much as 10 mm in length and 3 mm in width. Epidote (0.4 percent) occurs as discrete grains in association with biotite. Apatite, zircon, allanite, and opaques are common trace minerals.
GM-103A-69	42°38′08″ N. 107°30′58″ W.	Dark-gray, fine-grained amphibolite intercalated with quartzofeldspathic gneiss. Amphibolite has well-developed nematoblastic texture. Hornblende and plagioclase in a ratio of about 2:1 dominate the mineralogy. Quartz is an important varietal mineral. Most of the plagioclase is extremely fresh but local areas within the section show intense saussuritization. Opaques, apatite, epidote, and white mica are minor phases.
*GM-104-69	42°38′46″ N. 107°30′58″ W.	Light-gray, fine-grained, xenoblastic, equigranular granodioritic gneiss. The rock is foliated but only faintly banded with sparse leucocratic layers as much as 5 mm in width alternating with massive bands from 2 to several cm in width. The foliation of the rock is defined by alinement of the hornblende (8.9 percent). Biotite is not present, a feature that distinguishes this rock from the other quartzofeldspathic gneisses described herein. Plagioclase (38 percent), virtually unaltered, is more calcic (An_{37}) than in the other gneisses, but the rock contains significant amounts of microcline (9.4 percent). Accessory minerals include sphene (0.7 percent), epidote (0.3 percent), and apatite (0.2 percent). Quartz is 43 percent.
W2-CR-4(114)	42°36′40″ N. 107°46′10″ W.	Dark-gray, fine- to medium-grained amphibolite. Hornblende and plagioclase (An_{30}) in approximately equal amounts constitute most of the rock. Quartz, biotite, sphene, apatite, opaques, epidote, and white mica are present in small amounts. Plagioclase is, for the most part, fresh, but locally it is saussuritized. This sample is mineralogically and texturally similar to GM-103A-69 but is slightly coarser in grain size.
FCA-R-1	42°50′19″ N. 107°52′54″ W.	Medium-gray, medium- to coarse-grained, well-foliated granodioritic gneiss. Rock is not compositionally banded, but well-developed foliation is imparted by alined hornblende and biotite. Approximate mode: plagioclase, 40 percent; quartz, 30; hornblende, 15; biotite, 10; microcline, 5. Allanite, sphene, epidote, apatite, and zircon are accessory minerals. Altered allanite grains are commonly rimmed by epidote. White mica, epidote, chlorite, and carbonate are minor alteration minerals.

fragments. No outcrops of iron-formation had been identified in the region at that time.

The unit designated as quartzofeldspathic gneiss in figure 2 contains a variety of biotite-quartz-feldspar gneisses that are interlayered with subordinate amounts of mica schist, amphibolite, augen gneiss, epidote gneiss, and serpentinite. Most of the samples (table 1) used for radiometric dating of the metamorphic complex are from this unit.

The gneisses are characteristically well foliated and form a layered sequence of alternating and compositionally distinct units. The thickness of the layers ranges from a few centimeters to several meters. Migmatitic varieties contain thin discontinuous layers of leucocratic phases as much as a centimeter thick with sparse porphyroblasts of microcline. Locally, very tight small-scale folding is present in the gneisses, and layers of amphibolite have been distended to form boudins and rotated blocks. The gneisses are intruded by numerous dikes and stringers of granitic material, some of which have been deformed and metamorphosed. Other dikes are undeformed and are apparently related to the younger granite (fig. 2) that intrudes the metamorphic complex. Some of the biotite augen gneiss that is interlayered in places with the finer grained quartzofeldspathic gneisses is similar to that shown as a separate unit (fig. 2).

The compositional range of the gneisses is shown on figure 3. Using the nomenclature for igneous rocks (Streckeisen, 1973) without any genetic implications, the gneisses range in composition from tonalitic to granitic. The granitic gneisses are subordinate in volume to the tonalitic and granodioritic gneisses. In T. 31 N., Rs. 92-93 W., Sherer (1969) identified three major lithologies of gneisses—the dominant biotite gneiss, granite gneiss of uncertain relationship to the biotite gneiss, and quartzofeldspathic gneiss derived from granitic dikes and sills that are intrusive into both the biotite gneiss and granite gneiss. Gneisses in the granite field of figure 3 are mainly the granite gneiss and quartzofeldspathic gneiss of Sherer (1969).

Intense alteration adjacent to the zones of nephrite veins has produced a variety of epidote-rich gneisses similar to but generally coarser grained than the fine-grained epidote-rich gneiss of figure 2. Sherer (1969, 1972) concluded that the nephrite veins formed as a consequence of hydrous metasomatic alteration of amphibolite with iron, aluminum, and calcium being mobilized during this alteration to produce epidotization of the country rocks.

Much of the gneiss exposed in a series of low-lying hills centered in the area outlined by Tps. 30 and 31 N. and Rs. 91 and 92 W. is pervasively altered. In the field, a major lithologic unit was called "green" gneiss because of its faint greenish-gray color. Thin sections show that the gneiss contains 30 to 50 percent quartz, but the feldspar, presumably plagioclase, has been completely altered to fine-grained, felted aggregates of white mica. Sherer (1969) described similar alteration and has identified the secondary mica as paragonite. In one sample, biotite has been totally

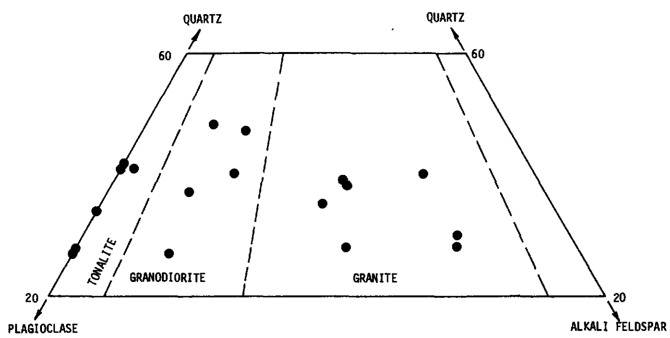


FIGURE 3.—Samples of quartzofeldspathic gneiss (dots) plotted on a portion of ternary diagram of modal quartz, plagioclase, and alkali feldspar with the IUGS classification for plutonic rocks (Streckeisen, 1973). Data are from Sherer (1969) and this report (table 1).

altered to chlorite that is dusted with fine-grained opaque inclusions, but in others the biotite is fresh, although it is extremely pale brown, suggestive of a low-iron content. Coarse muscovite occurs in one sample that transects the plagioclase relics and altered biotite. Epidote and zircon are trace constituents. Unaltered gneisses also occur in this area. Amphibolite and serpentinite layers are common but volumetrically small compared to the altered and unaltered quartzofeldspathic gneisses.

A variety of medium- to coarse-grained epidote-bearing gneisses occur throughout the metamorphic complex, but in T.31 N., Rs. 92 and 93 W., fine-grained epidote gneiss is mapped as a distinct unit (fig. 2). These rocks are extremely fine grained (0.1-0.5 mm), gray to pastel shades of green, yellow and pink gneisses that in outcrop resemble metarhyolite or fine-grained quartzite. They exhibit blocky fracturing and are extremely tough and brittle. The epidote gneisses are variable in composition but are characterized by quartz, epidote, and fresh to altered plagioclase. Some samples of the epidote gneiss contain significant amounts of actinolite both as poikiloblastic grains that include the other minerals and as fibrous aggregates. Compositional layering ranges from a few millimeters to several centimeters and results from variable epidote and actinolite concentrations. Granoblastic quartz-plagioclase layers alternate with strongly nematoblastic epidote- and actinolite-rich layers. One sample examined contains approximately equal amounts of epidote and quartz but no plagioclase. Sphene and apatite are ubiquitous accessory minerals. Aggregates of granular sphene are strung out in the direction of the foliation and are characteristically associated with epidote The origin of the epidote gneiss is problematic. Sherer (1969) related epidote-rich gneisses to alteration associated with the nephrite veins. The fine-grained epidote gneiss described here may have been derived from intermediate to silicic volcanic rocks, a speculation supported by its association with layered amphibolite, which is probably derived from a mafic volcanic rock.

Dark-gray, fine- to medium-grained amphibolite (fig. 2) occurs as thin, discontinuous layers throughout the metamorphic complex and is the dominant lithology in a northeasterly trending belt in T. 31 N., R. 93 W. and in the northwestern part of T. 30 N., R. 92 W. In both areas, but particularly in the latter, quartzofeldspathic gneiss is abundantly interlayered with the amphibolite. In these areas the amphibolite is commonly banded with alternating mafic and very thin more leucocratic layers, and weathers to produce slabby or flaggy outcrops. Detailed petrographic studies of the amphibolite were not completed, but a few thin sections show it to consist dominantly of plagioclase and hornblende, with minor amounts of quartz. Epidote, sphene, and apatite are common accessory minerals and trace amounts of biotite are present in some samples. Some of the amphibolite within the quartzofeldspathic gneisses is dominated by hornblende with only small amounts of plagioclase. In T. 31 N., R. 93 W., the amphibolite is pervaded by numerous dikes and sills of granite and pegmatite.

Dark-gray, fine-grained biotite gneiss (fig. 2) is poorly exposed in low-lying outcrops in the center of T. 31 N., R. 93 W. The rock is strongly foliated with 20 to 30 percent biotite and approximately equal amounts of quartz and sodic plagioclase, much of which is untwinned. Apatite, epidote, zircon, and opaques are accessory minerals. The biotite occurs as subparallel grains as much as 1 mm in length in a granoblastic mosaic composed of 0.1-0.2-mm grains of quartz and feldspar. Compositional banding in outcrop is presumed to represent relic sedimentary layering and the rock is interpreted to be, on the basis of this and the composition, a metagraywacke. In comparison with the quartzofeldspathic gneisses (fig. 2), this biotite gneiss unit is characterized by its finer grain size, greater abundance of biotite, and absence of K-feldspar. The metagraywacke is intruded by numerous small dikes and stringers of granitic rock and pegmatite. A similar rock type is intercalated in places with the quartzofeldspathic gneiss and with the amphibolite.

Medium- to coarse-grained biotite augen gneiss (fig. 2) occurs in many places throughout the metamorphic complex and is distinguished as a sizable unit in T. 31 N., Rs. 92, 93 W. The gneiss is strongly inequigranular with distinct augens as much as several centimeters in length. The augens are commonly composites of quartz, plagioclase, and poikiloblastic microcline. These are contained within a finer grained groundmass of mainly quartz, plagioclase, microcline, and biotite. Biotite is in lenticular aggregates and imparts a distinct but wavy foliation to the rock. Muscovite, epidote, sphene, apatite, zircon, opaques, and altered allanite are common accessory minerals. In places, the augen gneiss has been highly sheared and the augen have been stretched into long, recrystallized leucocratic streaks. Within the main outcrop area, the augen gneiss is extensively intruded by granitic and pegmatitic dikes that are undeformed.

GRANITE

The western part of a large granitic batholith crops out in the map area (fig. 2), where these rocks form a major part of the Precambrian. For purposes of discussion here, three masses of granite separated by metamorphic rocks are referred to as the granite at Long Creek Mountain (eastern part of T. 31 N., R. 94 W. and the northwestern part of T. 31 N., R. 93 W.), the granite at Tincup Mountain (a belt extending northeasterly across T. 31 N., R. 93 W.), and the granite of Lankin Dome (Tps. 29-30 N., Rs. 88-92 W.). The batholith extends eastward several kilometers beyond the limit of the map area. Excellent exposures of the granite occur in rounded to craggy knobs and hills that rise a few hundred meters above the plain of flat-lying Tertiary sedimentary rocks. The granite is clearly younger than the enclosing metamorphic rocks and both units are cut by diabase dikes. Samples that were used in the dating, a few of which are from outside the map area, are described in table 2.

The granite at Long Creek Mountain is a massive to foliated light-gray to reddish-gray biotite granite with inclusions and schlieren of biotite gneiss and amphibolite. Small dikes and stringers of pegmatite, aplite, and quartz are common throughout the body. At the north end of the mass, the granite becomes gneissic with faint banding, and an inclusion or screen of migmatite approximately 30 m thick was observed. The foliation in the gneissic phase strikes N. 50° E., parallel to the regional structure of the metamorphic rocks, but dips approximately 35° to the northwest. The granite at Long Creek Mountain was not sampled for Rb-Sr dating because of pervasive weathering, but U-Pb dating of zircons suggests that the granite may be slightly older than the granites of Lankin Dome and Tincup Mountain (K. R. Ludwig and J. S. Stuckless, oral commun., 1976).

The granite at Tincup Mountain is a fine- to medium-grained, medium-gray, foliated muscovite-biotite granite that is cut by numerous dikes of pegmatite, aplite, and quartz. Some of the aplite dikes are unusually garnetiferous, and very coarse grained muscovite-bearing pegmatite is present locally.

The granite of Lankin Dome is the main body of granite and is typically massive and medium to coarse grained. Dikes of pegmatite ranging from several centimeters to a meter or more in width are common. Phenocrysts of microcline as much as several centimeters in length are dispersed throughout the granite at spacings of a meter or more. Isolated pegmatitic clots as much as several tens of centimeters long are also common. The major rock type exposed contains approximately equal amounts of quartz, plagioclase, and perthitic microcline, which form 90-95 percent of the rock. Plagioclase composition ranges from albite to oligoclase, and the appropriate rock names are biotite granite and biotite alkali-feldspar granite, according to the IUGS classification (Streckeisen, 1973). The average composition of the biotite granite (Stuckless and others,

TABLE 2.—*Descriptions and modal analyses of granitic rocks*

[Asterisk by sample number indicates modal analysis by point counting (500 to 600 points). Other modes are visual estimates. Sample localities illustrated in figure 2]

Sample	Locality	Description
GM-55-68	42°32′03″ N. 107°53′06″ W.	Medium-grained, faintly foliated biotite granite collected from within 1.2 m of the contact with an 18-m-wide diabase dike. Contains approximately 40 percent plagioclase; 30 quartz; 20 microcline; 10 biotite; and trace amounts of epidote, white mica, chlorite, zircon, apatite, and opaques. Plagioclase is severely altered to white mica, and cryptoperthitic microcline is clouded with minute inclusions. Biotite is mainly fresh and appears to have been recrystallized, as cleavage lies at right angles to grain elongation in places. Epidote, commonly subhedral, generally occurs in association with the biotite. Alteration of the granite is apparently related to heating attendant with emplacement of the diabase.
GM-56-68	42°32′07″ N. 107°52′51″ W.	Hand specimen and thin section of this sample was inadvertently lost. Rock is described in field notes as a strongly foliated and locally sheared porphyritic granite intruded by stringers and dikes of pegmatite and biotite granite. Sample was collected for its fresh biotite.
GM-81-68	42°33′04″ N. 107°43′47″ W.	Light-greenish-gray, medium-grained epidotized granite. Contains approximately equal amounts of plagioclase (chessboard albite) and quartz (30-40 percent each), epidote (20 percent), and about 10 percent chlorite. Zircon and apatite are trace minerals. Epidote occurs both as composite aggregates and as discrete euhedral grains interspersed in quartz and feldspar. Anhedral to euhedral sphene is commonly in association with composite chlorite aggregates. Albite is locally poikilitic with numerous inclusions of quartz as well as epidote.
W2-CR-1(99)	42°41′50″ N. 107°19′46″ W.	Pinkish-gray, coarse-grained granite. Quartz, plagioclase and microcline, in roughly equal amounts, constitute about 90 percent of the rock. Chlorite, formed from biotite, is the next most abundant mineral. Epidote, sphene, apatite, zircon, opaques, and leucoxene occur in trace amounts. Plagioclase (albite or sodic oligoclase) shows faint zoning and is moderately to strongly saussuritized. Sphene, both as granular grains in chlorite and as discrete euhedral wedges, is strongly altered to leucoxene. Euhedral epidote grains occur in association with the mafic minerals. Microcline is fresh and commonly poikilitic with inclusions of quartz, plagioclase, and epidote. Composite grains of quartz are common with moderately sutured grain boundaries.
W2-CR-1(153)	42°41′50″ N. 107°19′46″ W.	Texturally and mineralogically similar to sample W2-CR-1(99) except not nearly as altered. Biotite, for the most part, is fresh with only a few grains showing alteration to chlorite. Plagioclase is somewhat altered to white mica but generally fresher than in W2-CR-1(99).
*W2-CR-14(101)	42°32′35″ N. 107°39′15″ W.	Light-gray, medium- to coarse-grained, inequigranular biotite granite. Quartz (29 percent) is strained and commonly occurs as composite grains with some suturing of grain boundaries. Microcline (33 percent) is fresh, strongly perthitic, and poikilitically includes quartz, plagioclase, and biotite. Plagioclase (An_{10-15}, 31 percent) is moderately altered to white mica, faintly zoned, and locally shows bent twin lamellae. Biotite (1.4 percent) is partially altered to chlorite (1.1 percent) and granular sphene. Epidote (1.6 percent) occurs mainly as subhedral grains in association with the mafic minerals, and muscovite is present as discrete grains (1.6 percent). Sphene, zircon, apatite, and opaques are present in trace quantities.
*W2-CR-14(157)	42°32′35″ N. 107°39′15″ W.	Texturally and mineralogically similar to W2-CR-14(101). Modal analysis: quartz, 34 percent, microcline, 36; plagioclase, 26; biotite, 1.4; chlorite, 1.4; muscovite, 1.1; epidote, 0.4; and trace amounts of sphene, zircon, opaques, and white mica.
*W2-CR-26(99)	42°33′46″ N. 107°22′09″ W.	Medium-grained, light-gray biotite granite. Quartz (26 percent) occurs as strained, composite grains with some sutured boundaries. Plagioclase (An_{12-15}, 29 percent) is moderately saussuritized with some bent and broken twin lamellae and healed mortar structure around larger grains. Perthitic microcline (37 percent) is fresh and commonly poikilitic with inclusions of quartz, plagioclase, and biotite. Biotite (5.1 percent) is partially altered to chlorite (0.3 percent) and traces of granular sphene. Epidote (1.5 percent) and opaques (0.2 percent) are commonly associated with the biotite aggregates. Sphene, zircon, apatite, white mica, and monazite (?) are present in trace amounts.
*W2-CR-26(165)	42°33′46″ N. 107°22′09″ W.	Generally similar to W2-CR-26(99). Modal analysis: plagioclase (zoned from An_8 to An_{19}, 34 percent); microcline, 31; quartz, 30; biotite, 2.6; epidote, 1.6; muscovite, 0.2; chlorite, 0.2; and trace amounts of monazite(?), zircon, apatite, opaques, carbonate, sphene, and white mica.
*ZW-263	41°31′02″ N. 107°48′04″ W.	Very light gray, coarse-grained, leucocratic porphyritic granite. Approximately 10 percent of the rock is composed of poikilitic microcline phenocrysts attaining lengths of 25 mm but more commonly about 10 mm. Groundmass is medium to coarse grained. Plagioclase (An_8, 32 percent) is altered to white mica and epidote and in places shows bent twin lamellae. Microcline (38 percent) is fresh and is poikilitic in both the groundmass and phenocryst phases with inclusions of quartz, plagioclase, and epidote. Quartz (28 percent) is strained and commonly forms composite grains. Biotite (0.3 percent), chlorite (0.2 percent), and epidote (0.3 percent) are commonly associated. Granular sphene in chlorite, zircon, and opaques are trace minerals. Muscovite (0.3 percent) occurs as discrete grains but commonly restricted to the plagioclase.
*D1686	42°39′00″ N. 107°54′30″ W.	Light-gray, medium-grained, faintly foliated biotite granite. Quartz (27 percent) is strained with some sutured boundaries in composite grains. Plagioclase (albite or sodic oligoclase, 34 percent) is moderately altered to white mica and in places shows bent twin lamellae. Microcline (30 percent) is commonly poikilitic. Biotite (4.4 percent) is slightly chloritized (0.3 percent). Muscovite (2.9 percent) is a significant varietal mineral. Epidote, zircon, allanite, garnet, and opaques are trace constituents.

TABLE 2.—*Descriptions and modal analyses of granitic rocks*—Continued

Sample	Locality	Description
*DDH-1	42°31′00″ N. 107°38′30″ W.	Light-gray, medium-grained biotite granite with some iron staining. Plagioclase (albite or sodic oligoclase, 37 percent) is moderately saussuritized with bent twin lamellae locally. Quartz (37 percent) is in strained composite grains showing some incipient mortar structure in places. Microcline (22 percent) is fresh and commonly poikilitic. Subhedral grains of epidote (0.5 percent) are associated with slightly chloritized biotite (3.4 percent). Muscovite (0.4 percent) occurs both as discrete grains and in the alteration products of plagioclase. Apatite, zircon, and opaques are trace constituents.
DDH-2	42°32′55″ N. 107°49′14″ W.	Light-gray, medium-grained biotite granite. Approximately 95 percent of the rock comprises nearly equal amounts of quartz, plagioclase, and microcline. Biotite, somewhat chloritized, is the major varietal mineral. Plagioclase is somewhat saussuritized. Epidote also occurs as discrete subhedral grains associated with biotite. A few grains of monazite are present. Protoclasis is indicated by bent and broken twin lamellae in plagioclase and incipient mortar structure.
D114944 D114945	42°10′27″ N. 106°52′47″ W.	Light-gray, medium-grained biotite granite collected from the abutment of the Kortes Dam (Rosholt and Bartel, 1969). Hand specimens of these particular samples are not available but others from the area show marked similarity to samples from the granite of Lankin Dome.
256179	42°18′28″ N. 106°50′46″ W.	Drill core of coarse-grained biotite granite from the Little Man mine. Described in Rosholt and Bartel (1969).
GM-1	42°32′35″ N. 107°39′15″ W.	Medium- to coarse-grained, leucocratic granite from USGS drill hole GM-1 (Stuckless and others, 1977). Descriptions of samples and modes are given by Stuckless and others (1976). Abundances of the major minerals, in percent, are listed below:

Sample		Quartz	Plagioclase	Microcline	Biotite
GM-1	(739)	29	43	23	1.8
	(771)	37	30	31	.6
	(891)	30	20	45	2.0
	(1021)	39	37	21	2.1
	(1156)	39	59	0	2.3

1977) is 31 percent quartz, 30 percent plagioclase, 34 percent microcline, and 5 percent biotite and chlorite, with alteration and accessory minerals constituting less than 2 percent.

Texturally, the biotite granite is allotriomorphic inequigranular. Perthitic microcline is poikilitic with inclusions of plagioclase, quartz and biotite. Plagioclase is altered to white mica and granular epidote. Epidote also occurs as subhedral grains in association with clusters of biotite and opaque minerals. Biotite shows all degrees of alteration to chlorite and granular sphene, which is partially altered to leucoxene. Quartz occurs as composite grains with marked undulatory extinction, and some sections show sutured grain boundaries within the quartz composites. Protoclastic textures are further evidenced by bent and broken twin lamellae in plagioclase. Zircon, apatite, allanite, monazite, and opaques are common accessory minerals.

Stuckless and others (1977) identified a second major phase of the granite that was encountered in a drill hole but is not exposed or at least was not recognized in outcrop. These authors described the rock as a leucocratic phase with an average modal composition of 38 percent quartz, 29 plagioclase, 30 microcline, 1.2 biotite, 1.2 muscovite and minor amounts of epidote, garnet, opaques, and other accessory minerals. The leucocratic phase is significantly lower in Th, Fe, Sr, and Rb than the biotite granite (Stuckless and others, 1977).

The granite is locally foliated at the western end of the batholith, where it is in contact with the metamorphic rocks and forms a mixed zone of granite and gneiss. The metamorphic rocks have been extensively intruded by numerous dikes and sills of pegmatite, aplite, and fine- to medium-grained granite. The metamorphic rocks adjacent to the granite at Long Creek Mountain and the granite at Tincup Mountain are pervaded in similar fashion by abundant granitic material.

In addition to the minor cataclasis and alteration that has occurred in the biotite granite, intense alteration has taken place along linear zones within the batholith. Here the granite has been strongly epidotized and converted to an extremely tough and brittle rock. The zones of epidotized granite stand above the unaltered granite as resistant ridges and are characterized by a blocky fracture pattern. Stuckless and others (1977) described this alteration and referred to the zones as being silicified and epidotized. Epidotization seems to be the dominant alteration in samples examined during the present study. Biotite and microcline, which are ubiquitous in the biotite granite, are sparse or lacking in the alteration zones. Plagioclase is altered and epidote has been introduced in significant quantities. The allochemical nature of the alteration is exemplified by the mineralogy and by the Rb and Sr contents. The biotite granite contains approximately 200 ppm Rb and 100 ppm Sr, whereas a sample of epidotized granite (GM-81-68, table 4) derived from the biotite granite has 2 ppm Rb and 700 ppm Sr. An epidote separate from this sample contains approximately 1,000 ppm Sr. Significant amounts of material were added to and removed from the biotite granite to accomplish this alteration. It is likely that hydrothermal fluids of undefined nature and source rose along fractures within the granite to produce the extensive exchange of material and alteration that occurred. It is not known whether or not significant movement occurred along these fractures. As mentioned earlier, similar alteration has modified rocks of the metamorphic complex in places, especially in areas of nephrite mineralization.

DIABASE

Dikes of fine- to medium-grained diabase (fig. 2) intrude the granite and the metamorphic complex with a dominant east-northeast trend. The dikes range in width from less than a meter to several tens of meters. The dikes are chilled against the granite and metamorphic rocks and the wider dikes have baked the enclosing rocks, producing a contact zone that is commonly more resistant to weathering than either the diabase or the unaltered granite and gneiss. Sherer (1969) described variable degrees of alteration in the dikes, which he attributed to late-stage deuteric processes. The sample collected for dating in the present study is remarkably fresh, with olivine and pyroxene as mafic minerals and completely unaltered labradorite as the feldspar. The texture is subophitic with approximately equal amounts of plagioclase and pyroxene. Sparse grains of olivine are rimmed and veined with an opaque mineral.

GEOCHRONOLOGY

Most of the radiometric dating was done by the Rb-Sr method on whole-rock and mineral samples. Outcrops were sampled only where least weathered rock could be obtained; hence, the sampling is not representative of the actual lithologic abundances because of variable weathering susceptibilities of the rock types. A few core samples were obtained from holes that were sponsored by the Space and Missile Systems Organization (SAMSO) (Saucier, 1970) and by the U.S. Geological Survey (Stuckless and others, 1976).

The greatest part of the Rb-Sr analytical work was completed from late 1968 through 1970, following procedures described by Peterman, Doe, and Bartel (1967). During this period, 26 analyses of the Eimer and Amend strontium were made, and an average $^{87}Sr/^{86}Sr$ of 0.70797±0.00010 (1 standard deviation) was obtained. Duplicate analyses of rock samples completed about this same time indicate an uncertainty in the $^{87}Sr/^{86}Sr$ ratio of ±0.00026 (1 s.d.). This uncertainty is substantially greater than that of the standard and the increased variance is thought to be related to additional errors attendant in obtaining 0.2-0.5-gram aliquots of sample from material that contains minerals with drastically different $^{87}Sr/^{86}Sr$ values, that is, slight sample inhomogeneity problems. Duplicate $^{87}Rb/^{86}Sr$ values, also obtained on rock samples, indicate a coefficient of variation of ±1.3 percent of the ratio. These uncertainties are used in regressing the data by the method of McIntyre and others (1966). Uncertainties in the ages and initial $^{87}Sr/^{86}Sr$ values obtained from the regressions are given at the 95-percent confidence level.

The isotopic and decay constants used in calculating the ages are those recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1977). Ages herein quoted from published reports are recalculated using these constants where necessary.

METAMORPHIC COMPLEX

Rb and Sr data (table 3) when plotted on an isochron diagram (fig. 4) show scatter beyond experimental uncertainty, especially for samples with $^{87}Rb/^{86}Sr$ values of less than 0.8. However, the data can be separated into two groups on both statistical and geological grounds, and a reasonably precise isochron is obtained by eliminating samples FCA-R-1, CR-4(114), GM-103, and GM-98 from the regression. (Sample numbers are shortened for convenience here and in subsequent discussions.) The slope of the isochron based upon the remaining samples corresponds to an age of 2,860±80 m.y., and the initial $^{87}Sr/^{86}Sr$ is 0.7048±0.0012. The data for this regression still show slight variance in excess of experimental uncertainty (MSWD=3.54), and a Model III fit is used. (See McIntyre and others (1966) for explanations of the terminology and the statistical calculations.) NKomo and Rosholt (1972) determined whole-rock U-Th-Pb analyses on some of the same samples used in our study and obtained a $^{207}Pb/^{206}Pb$ age of 2,910±120 m.y.

Of the four samples that are excluded from the regression, GM-103 and CR-14(114) are amphibolites that are interlayered with the quartzofeldspathic gneisses. Samples FCA-R-1 and GM-98 are gneisses collected outside of the map area (fig. 2), in T. 33 N., R. 88 W., and T. 30 N., R. 95 W., respectively. These are well-foliated but massive gneisses that have only faint or no compositional banding in outcrop. In contrast, all of the data that define the main isochron (solid line, fig. 4) were obtained from layered gneisses. A reference isochron (dashed line, fig. 4) is drawn parallel to the main isochron through the four samples that are excluded from the regression. This reference isochron intersects the ordinate at 0.7017, a value significantly lower than the initial $^{87}Sr/^{86}Sr$ of 0.7048 for the main isochron.

Coexistence of rocks with different primary $^{87}Sr/^{86}Sr$ ratios that have maintained an isotopic identity through periods of amphibolite-grade metamorphism has been

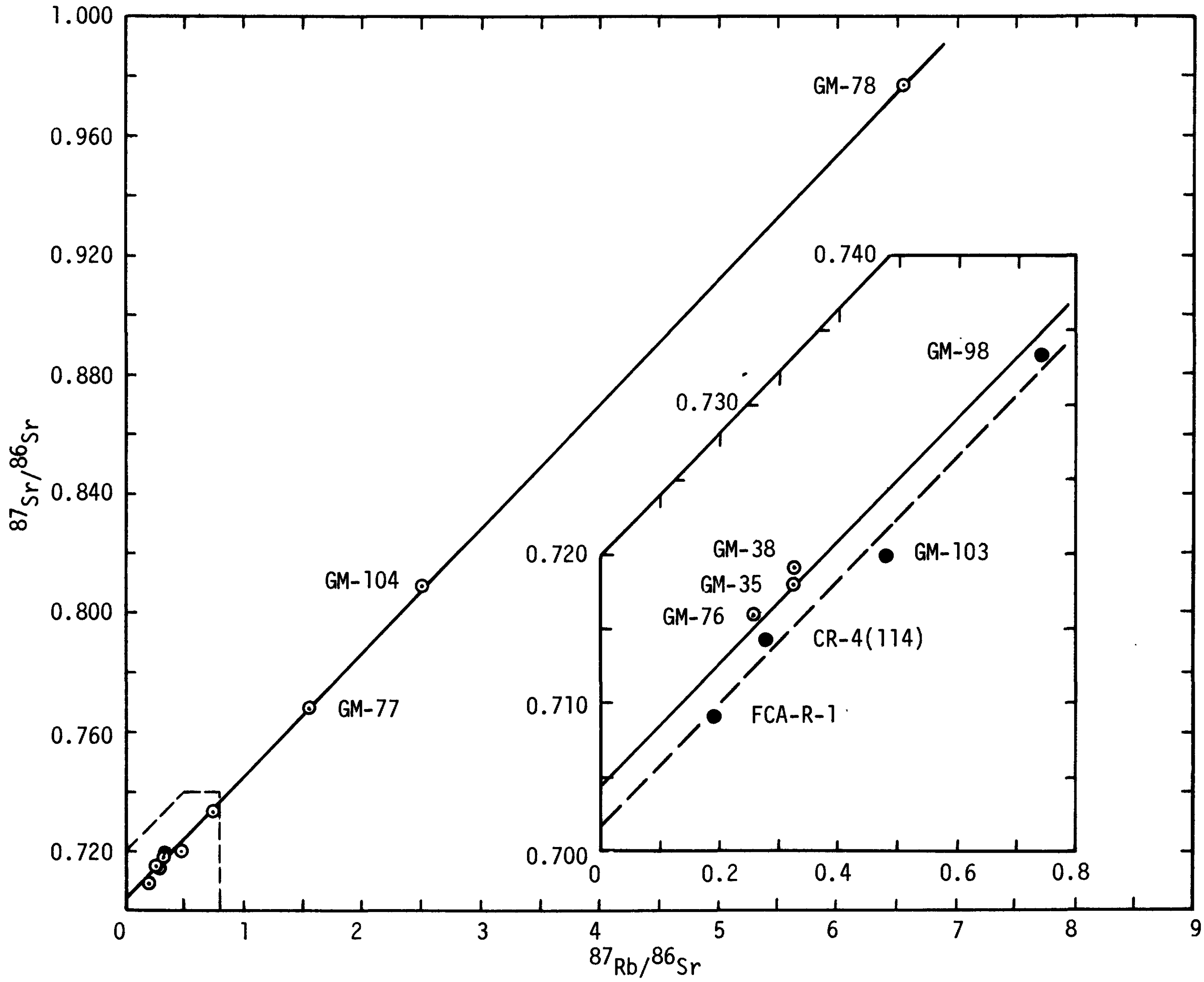


FIGURE 4.—Rb-Sr isochron plot for samples from the metamorphic complex. Rock types and modes are given in table 1. Solid circles, amphibolites (GM-103, CR-4(114)) and massive gneisses (FCA-R-1); open circles with dots, layered gneisses. Solid isochron corresponds to an age of 2,860±80 m.y. with an initial $^{87}Sr/^{86}Sr$ value of 0.7048±0.0012. Dashed line is a reference isochron drawn parallel to the solid isochron but with an initial $^{87}Sr/^{86}Sr$ value of 0.7017.

observed elsewhere. Subparallel isochrons for associated paragneisses and orthogneisses that were metamorphosed 1,710 m.y. ago were determined by Hedge, Peterman, and Braddock (1967) on rocks of a metamorphic complex of north-central Colorado. The metasedimentary rocks have an initial $^{87}Sr/^{86}Sr$ of 0.7079 whereas the orthogneisses, including amphibolite, have a lower initial of 0.7021. Hofmann and Köhler (1973) observed similar differences between orthogneisses and diatexites—gneisses in intermediate and advanced stages of anatexis—of the Schwarzwald of southwest Germany. Thus, it is possible that the massive gneisses of the Granite Mountains have a different origin than gneisses of the layered sequence and that primary differences in the isotopic composition of the common Sr were at least partially preserved during the metamorphism.

Inherent uncertainties in interpreting Rb-Sr isochron ages defined on whole-rock samples of metamorphic rocks may be considerably greater than in interpreting similar data for plutonic igneous rocks. The collinearity of data on the main isochron of figure 4 implies that the samples shared a uniform or nearly uniform composition of common Sr at 2,860 m.y. ago. The major problem is interpreting the geologic significance of this age. We will not attempt to

TABLE 3.—*Analytical data for metamorphic rocks*

Sample No.[1]	Rb (ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
GM-35-68R	44.3	398	0.322	0.7179
GM-38-68R	37.6	338	.323	.7191
GM-76-68R	28.0	318	.255	.7149
GM-77-68R	91.0	171	1.550	.7680
GM-78-68R	212	96.0	6.55	.9773
GM-78-68Mi	401	102	11.90	1.1348
GM-78-68Pl	78.9	155	1.497	.8449
GM-78-68Bi	1,299	17.9	403	10.088
GM-98-68R	67.2	264	.739	.7328
GM-98-68Pl	8.45	375	.065	.7093
GM-98-68Bi	662	14.4	246	9.379
GM-103A-69R	19.0	114	.479	.7198
GM-104-69R	61.3	71.1	2.50	.8091
W2-CR-4(114)R	11.3	118	.278	.7142
FCA-R-1-69R	44.6	686	.188	.7090

[1]Suffix letters on sample number indicates type of sample analyzed: R, whole rock; Pl, plagioclase; Mi, microcline, Bi, biotite.

review all of the literature pertinent to this problem but only mention a few studies that have particular bearing on our interpretation.

Impure sedimentary rocks such as shales and graywackes, and volcanic rocks that are subjected to prograding metamorphism will undergo a series of physical and mineralogical changes until the highest pressure-temperature conditions are attained, at which time a stable mineral paragenesis may be approximated (Winkler, 1974). A fluid phase may be particularly important in facilitating the mineralogic reactions and in modifying the compositions of the rocks through dewatering (Norris and Henley, 1976). Thus, ample opportunity exists for open system conditions to obtain, beginning with diagenesis, through the final stages of metamorphism. Indeed, a number of studies have shown that whole-rock Rb-Sr systems of sedimentary and volcanic rocks are highly susceptible to partial or complete resetting during postdepositional metamorphism (Pidgeon and Compston, 1965; Compston and others, 1966; Peterman, 1966; Turek and Stephenson, 1966; Lanphere, 1968; Turek and Peterman, 1968; Gorokhov and others, 1970; Clauer and Bonhomme, 1970; Hofmann and Grauert, 1973; Lyon and others, 1973; Gebauer and Grünenfelder, 1974). Some of these studies show that only relatively low grades of metamorphism are required to disturb the Rb-Sr systems. The results obtained by Pidgeon and Compston (1965) are particularly important in interpreting and understanding whole-rock Rb-Sr ages of metamorphic rocks. They analyzed a series of metasedimentary rocks that circumscribe a granitic intrusion and increase in grade from the chlorite zone to migmatitic rocks of amphibolite facies. The whole-rock ages decrease toward and become concordant with the age of the granite in the cordierite-orthoclase and migmatitic zones. Hofmann and Grauert (1973) found similar systematics in a progressively metamorphosed contact zone within Belt Supergroup sedimentary rocks that are intruded by an early Tertiary phase of the Idaho batholith. Their results demonstrated a systematic lowering of ages obtained on small whole-rock samples (1-2-cm-thick slabs), with some complexities, and the ages were totally reset in the sillimanite-muscovite zone.

The complex mineralogical changes and the disturbances in the Rb-Sr systems that occur during prograding metamorphism strongly suggest that whole-rock Rb-Sr isochrons obtained on intermediate to high-grade rocks can be assumed to approximate the time of metamorphism; that is, the time that these rocks attained their stable or near-stable mineral assemblages. Once the rocks have gone through a cycle of metamorphism that produced a relatively simple mineral suite, such as quartz+plagioclase+biotite±K-feldspar±garnet in a metagraywacke, the Rb-Sr whole-rock systems may remain closed or respond in a manner similar to those of granitic rocks during subsequent metamorphic events. Even in complexly banded gneisses, individual bands may retain their isotopic integrity through rather severe later metamorphism (Jäger, 1970; Krogh and Davis, 1973; Grauert and others, 1974; Hänny and others, 1975; Steiger and others, 1976), although exceptions have been documented and the scale of compositional banding is a particularly critical factor (Grauert and Hall, 1974; Hänny and others, 1975). If severe shearing and recrystallization occurs during the later metamorphism, the Rb-Sr systems may be partially or totally reset (Zartman and Stern, 1967; Hanson and others, 1969; Hunziker, 1970; Turek and Peterman, 1971; Abbott, 1972; Sims and Peterman, 1976).

Although the effects of cataclasis are recognized locally in the metamorphic complex of the Granite Mountains such as in the augen gneiss (fig. 2), the samples collected for radiometric dating have not been sheared subsequent to their metamorphism (table 1). All of the samples were collected from bands that are uniform in composition over a half meter or more and none were taken in proximity to major lithologic boundaries. In view of these factors and the previous results obtained on studies of metamorphic rocks, we interpret the whole-rock Rb-Sr age of 2,860±80 m.y. as representing the time of major regional metamorphism. All of the Precambrian rocks of the area have been subjected to a late Precambrian X or early Precambrian Y cryptic thermal event that has disturbed the Rb-Sr mineral systems. This later thermal event does not seem to have affected the whole-rock Rb-Sr systems of the gneisses to any great extent, although some of the excess scatter on the isochron plot (fig. 4) may have resulted from this heating.

The initial $^{87}Sr/^{86}Sr$ value of 0.7048±0.0012 determined for the main isochron (fig. 4) suggests that the protoliths of the gneisses may have had a significant crustal history prior to the major metamorphism. The crustal residence time of the Sr can be estimated if we assume that the six gneisses defining the isochron, admittedly a small and biased sampling, are approximately representative of the gneiss terrane as a whole and that the Rb/Sr ratios have not been drastically modified by the metamorphism. The mean $^{87}Rb/^{86}Sr$ ratio of the tonalitic and granitic gneisses is 0.94. An Rb-Sr system with this ratio and an $^{87}Sr/^{86}Sr$ value of 0.7048 at 2,860 m.y. ago would have separated from the mantle or mantle-like (in terms of Rb/Sr) source between 3,200 and 3,300 m.y. ago. Geologic models can be invoked to agree with this isotopic speculation. A volcanic pile or a sedimentary sequence, or combination thereof, could have formed with mantle-like $^{87}Sr/^{86}Sr$ ratios a few hundred million years before the major metamorphic event. The presently observed initial ratio of 0.7048 would be the consequence of isochron rotation during the metamorphism. Alternatively, a sedimentary pile could have been deposited just shortly before the metamorphism, and the initial ratio of 0.7048 would have resulted through the derivation of these rocks from a crustal terrane that was several hundred million years older. The assumptions in this simplistic interpretation contain many uncertainties; nevertheless, a premetamorphic crustal residence time of several hundred million years is suggested for the Sr contained in the protoliths.

GRANITE

Twenty samples of granitic rocks were analyzed for Rb-Sr dating (fig. 5, table 4). Several of these samples are from granite bodies that lie outside of the map area (fig. 2). Samples 114944 and 114945 from the Seminoe Mountains, and 256179 from the Pedro Mountains were described briefly by Rosholt and Bartel (1969). These localities are 40-50 km southeast of the southeastern corner of the area covered by figure 2. Samples W2-CR-1(99) and W2-CR-1(153) are from a SAMSO drill hole in the southern part of T. 32 N., R. 88 W.

All of the Rb-Sr data are plotted in figure 5 with the open circles representing core samples and the solid circles representing surface samples. Two core samples (DDH-1 and DDH-2) were collected with a Winkie drill and are considered to be surface samples because of the shallow depth from which they were obtained.

A number of the data points depart from colinearity by considerably more than analytical error (fig. 5). Regression of all the points (20) results in a Model IV isochron with an age of 2,500±70 m.y. and initial $^{87}Sr/^{86}Sr$ ratio of 0.7074±0.0045. By deleting all data points that deviate substantially from the isochron (samples GM-1(1156), GM-1(1021), ZW-263, GM-81, DDH-1, DDH-2, GM-55, and 256179), regression of the remaining data (12 points) results in a Model I fit with an age of 2,540±30 m.y. and an initial Sr ratio of 0.7051±0.0013. The statistical screening has some geologic meaning as suggested by the fact that it resulted in elimination of data for many of the surface samples.

The granite weathers more readily than do the gneisses of the metamorphic complex, and surface samples of the granite commonly show some effect of weathering, such as iron staining. The scatter of data for some of the surface samples (fig. 5) indicates that weathering indeed has had a deleterious effect on the Rb-Sr systems. The whole-rock Rb-Sr systems are particularly susceptible to disturbance because the constituent minerals yield ages that are discordant with respect to the whole-rock ages. Thus, open-system behavior in the mineral Rb-Sr systems as a consequence of weathering can result in a shift of the whole-rock data point away from the isochron.

However, additional complexities are indicated because some of the fresh-appearing core samples also deviate from the isochron by more than experimental error. GM-1(1156) is a plagioclase-rich phase of the leucogranite and contains no microcline (table 2). Thus, the sample may have acted as a receptor or sink for radiogenic ^{87}Sr that was mobilized during the cryptic thermal event that disturbed the mineral systems, and the position of the data point above the isochron (fig. 5) is consistent with this speculation. GM-1(1021) does not have an unusual modal composition, and the reason for its departure from the isochron is not known.

TABLE 4.—*Analytical data for granitic rocks*

[Rb and Sr concentrations for GM-81-68R/Ep and GM-55-68R were determined by XRF analyses; all others were determined by isotope dilution]

Sample No.[1]	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
GM-55-68R	126	272	1.35	0.7481
GM-56-68Bi	404	19.2	69.4	2.155
GM-81-68R	2	724	.008	.7073
GM-81-68Ep	2	1,090	.005	.7070
W2-CR-1(99)R	136	254	1.545	.7607
W2-CR-1(153)R	115	289	1.149	.7481
W2-CR-14(101)R	241	87.5	7.98	.9989
W2-CR-14(157)R	223	95.6	6.92	.9632
W2-CR-14(157)Mi	445	111	11.96	1.0760
W2-CR-26(99)R	169	117	4.25	.8603
W2-CR-26(165)R	176	124	4.19	.8606
W2-CR-26(165)Mi	357	137	7.72	.9483
ZW-263R	133	85.2	4.53	.8606
ZW-263Mi	421	97.0	13.02	1.0841
D1686R	166	83.8	5.84	.9169
D1686Mi	465	155	8.96	1.0100
D1686Pl	49.5	126	1.145	.7612
D1686Bi	736	22.6	136.2	5.277
D1686Mu	486	15.1	132.7	5.098
DDH-1R	146	40.6	10.76	1.0752
DDH-2R	111	196	1.643	.7717
D114944R	197	80.1	7.31	.9750
D114944Mi	547	54.6	31.3	1.4977
D114945R	192	85.1	6.70	.9491
D114945Mi	356	37.3	29.7	1.4321
256179R	113	154	2.14	.7899
256179Mi	447	215	6.14	.8965
GM-1(739)R	191	17.0	37.0	2.0844
GM-1(771)R	221	30.5	22.7	1.5371
GM-1(771)Mi	425	47.4	28.5	1.7006
GM-1(891)R	143	27.6	15.86	1.2811
GM-1(1021)R	99.2	35.5	8.33	.9964
GM-1(1156)R	33.3	40.4	2.41	.8051

[1]Suffix letters on sample number indicate type of sample analyzed: R, whole rock; Pl, plagioclase; Mi, microcline; Bi, biotite; Mu, muscovite; Ep, epidote.

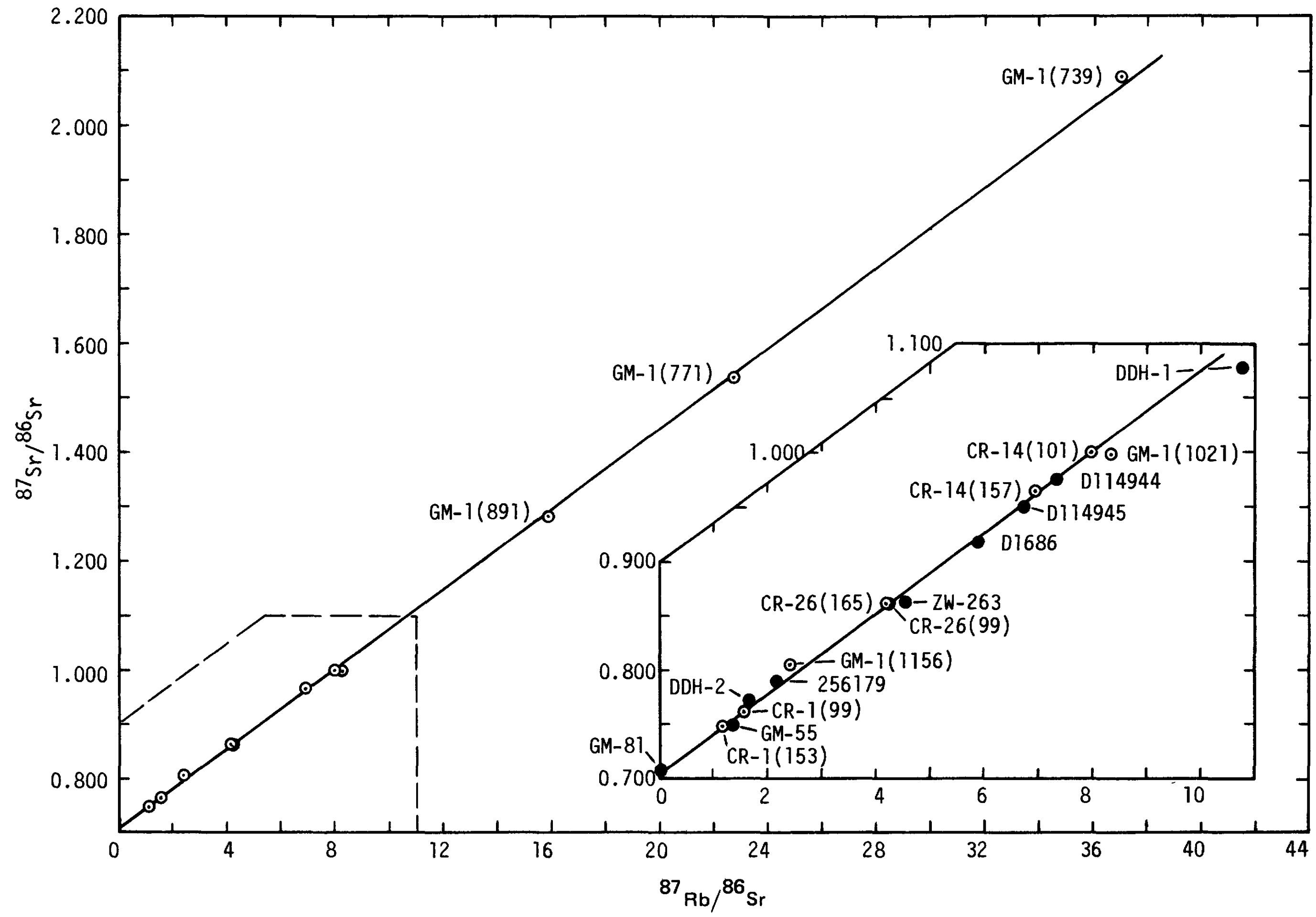


FIGURE 5.—Rb-Sr isochron plot for samples of granite rocks. Open circles represent core samples; solid circles represent surface or near-surface samples. Regression of selected data points as outlined in the text gives an age of 2,550±60 m.y. with an initial $^{87}Sr/^{86}Sr$ of 0.7053±0.0056.

One further selection of data points can be made solely on the basis of geologic grounds. If some surface samples are isotopically disturbed by weathering, the data for all surface samples can appropriately be excluded from the regression. Similarly, data for samples that were not taken from the main body of granite (fig. 2), granite of Lankin Dome, can be deleted. The resultant regression, based only on data from cores (7 samples) gives an age of 2,550±60 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7053±0.0056. It should be emphasized that none of these screening procedures changes the whole-rock isochron age significantly. In the last regression, which is a Model I fit, the 95-percent confidence levels on both the age and intercept are increased significantly because of the smaller number of samples.

Rosholt, Zartman, and NKomo (1973) reported a whole-rock $^{207}Pb/^{206}Pb$ isochron age of 2,750±80 m.y. for the granite. They interpreted this as a maximum age because of loss of uranium from the rocks in the Cenozoic. Data obtained on additional samples of the granite have lowered the whole-rock $^{207}Pb/^{206}Pb$ age slightly, and it is in better agreement with the Rb-Sr age (Stuckless and others, 1975).

T. W. Stern (written commun., 1976) determined U-Th-Pb ages of zircon from the granite at Tincup Mountain (D1686):

U=1,250 ppm	$^{208}Pb/^{204}Pb$=81.47
Th=1,363 ppm	$^{207}Pb/^{204}Pb$=0.2364
Pb=565 ppm	$^{206}Pb/^{204}Pb$=184.9

Ages based on a common Pb correction using a 2,500-m.y. composition are:

$^{206}Pb/^{238}U$=1,635 m.y.
$^{207}Pb/^{235}U$=2,075 m.y.
$^{207}Pb/^{206}Pb$=2,540 m.y.
$^{208}Pb/^{232}Th$=1,395 m.y.

Although the ages are discordant, they are in agreement with the Rb-Sr age of the granite if it is assumed that the data lie on a chord that intersects concordia at a reasonable lower value; that is, 50-100 m.y. K. R. Ludwig and J. S. Stuckless (written commun., 1976) have determined an age of 2,595±40 m.y. on zircons from the granite of Lankin Dome and on similar granites that crop out east of the map area (fig. 2). Data for the zircon at Tincup Mountain plot on the same chord as their data. They report a slightly older age of 2,640±20 m.y. for zircon from the granite at Long Creek Mountain.

On the basis of the Rb-Sr whole-rock data and the additional radiometric evidence from U-Th-Pb whole rock and zircon studies, we conclude that the granite at Tincup Mountain and the granite of Lankin Dome are coeval and were emplaced 2,550 m.y. ago. We also suggest that the granites represented by samples from drill hole W2-CR-1 and the granites of the Pedro and Seminoe Mountains represented by samples 256179, 114944 and 114945 (table 4) were emplaced at approximately this time.

The emplacement of these granites appears to be part of a major period of granitic plutonism, in the strict sense, in the Precambrian of western and southern Wyoming. (See summary of ages by Reed and Zartman, 1973.) Ages of major granitic bodies of this region are as follows:

	million years
Granite Mountains:	
Granites of Lankin Dome and Tincup Mountain	
Whole rock Rb-Sr (this report)	2,550±60
Zircon U-Pb (Ludwig and Stuckless, written commun., 1976)	2,595±40
Wind River Mountains, Bears Ear pluton:	
Zircon U-Pb (Naylor and others, 1970)	2,570±15
Teton Range, Mount Owen Quartz Monzonite:	
Whole rock Rb-Sr (Reed and Zartman, 1973)	2,440±75
Sierra Madre, Baggot Rocks Granite:	
Whole rock Rb-Sr (Divis, 1976)	2,500±100
Medicine Bow Mountains, Baggot Rocks Granite:	
Whole rock Rb-Sr (Hills and others, 1968)	2,430±50
Laramie Range, granite:	
Whole rock Rb-Sr (Hills and Armstrong, 1974)	2,490±40
Whole rock Rb-Sr (Johnson and Hills, 1976)	2,510±25

This period of granitic plutonism in southern and western Wyoming occurred slightly but distinctly later than tonalitic to granitic plutonism in the Superior Province of northern Minnesota and adjacent Ontario, where a number of intrusions are well dated at between 2,650 and 2,700 m.y. (Goldich, 1972). The dominantly granodioritic Louis Lake batholith of the Wind River Mountains, dated at 2,650±15 m.y. by Naylor and others (1970), is the approximate temporal equivalent of the Precambrian W intrusions of northern Minnesota.

The 2,450- to 2,600-m.y.-old granitic intrusions of Wyoming also differ from the silicic intrusions of northern Minnesota in that their initial $^{87}Sr/^{86}Sr$ ratios are consistently higher. When normalized to a common value of 0.7080 for $^{87}Sr/^{86}Sr$ of the Eimer and Amend standard, the initial ratios for the Wyoming granites are: (1) 0.7053 for granite of the Granite Mountains (this report), (2) 0.7022 for granite of the northern Laramie Range (Johnson and Hills, 1976), (3) 0.7044 for granite of the southern Laramie Range (Hills and Armstrong, 1974), (4) 0.7046 for the Baggot Rocks Granite of the Medicine Bow Mountains (Hills and others, 1968), (5) 0.7010 for the Baggot Rocks Granite of the Sierra Madre (Divis, 1976), and (6) 0.732 for the Mount Owen Quartz Monzonite of the Teton Range (Reed and Zartman, 1973). These contrast with initial ratios consistently between 0.7000 and 0.7010 for the Minnesota granitic rocks (Hanson and others, 1971; Prince and Hanson, 1972; Peterman and others, 1972; Jahn and Murthy, 1975).

To explain the unusually high initial $^{87}Sr/^{86}Sr$ ratio for the Mount Owen Quartz Monzonite, Reed and Zartman (1973) suggested that older crustal rocks were somehow involved in the genesis of the quartz monzonite, even though the country rocks did not have sufficiently high $^{87}Sr/^{86}Sr$ values at 2,500 m.y. ago to account for the extremely high initial of the quartz monzonite. Whatever the exact mechanism may have been, it seems likely that older crustal rocks may have been involved to varying degrees in the genesis of the Wyoming granitic rocks.

Alteration of the granite as manifested by linear zones of epidotization has not been directly dated in the present study. However, some reasonable inferences are in order. Similar alteration in the metamorphic complex is associated with nephrite mineralization, which, as shown in the following section, is dated at 2,510 m.y. In addition, Rb and Sr analyses were completed on a whole-rock sample of strongly epidotized granite and epidote separated therefrom (table 4, GM-81-68). Nearly all of the Rb has been removed and Sr has been enriched by almost an order of magnitude during the alteration. The $^{87}Sr/^{86}Sr$ ratios of 0.7070 and 0.7073 for the epidote and the whole-rock sample respectively are virtually identical and are indistinguishable from the initial $^{87}Sr/^{86}Sr$ ratio of the whole-rock isochron (fig. 5). If it is assumed that the Sr was derived locally, it had to have been separated from Rb only shortly after the granite crystallized. For example, if we take the average Rb/Sr value of the biotite granite as 1.9 and the isochron intercept at face value, the Sr in the epidotized granite would had to have been separated from a system with this mean Rb/Sr value within a few tens of millions of years after the granite crystallized. More precise calculations are unwarranted because of the large uncertainty in the initial $^{87}Sr/^{86}Sr$ ratio of the granite. Based upon these calculations and the relationship of epidotization in other rocks with the nephrite mineralization, we conclude that this alteration occurred between 2,500 and 2,600 m.y. ago.

DIABASE DIKES AND NEPHRITE VEINS

Conventional K-Ar ages of approximately 1,600 m.y. were previously reported (Peterman and others, 1971) for diabase and nephrite veins in the Granite Mountains. These ages are now known to be erroneous because of the difficulty in determining the potassium contents at the very low concentrations present—approximately 0.03 percent K_2O in labradorite from the diabase and 0.01 percent in the nephrite. G. B. Dalrymple and M. A. Lanphere (written commun., 1976) determined $^{39}Ar/^{40}Ar$ ages of approximately 2,600 m.y. on these same mineral separates (table 5). The diabase from which the separate of labradorite was obtained is described in an earlier section. The sample of nephrite was obtained from R. G. Coleman and was sawed from a piece of massive nephrite that occurred in a vein approximately 10 cm wide. A 2-cm cube was crushed and a sized fraction of -40 and +80 was prepared. The material was repeatedly washed with distilled water to remove the fines.

We conclude from these data that both the diabase and the nephrite veins were emplaced only shortly after the granite was intruded. Older mafic dikes that are metamorphosed occur in the metamorphic complex, but it is not known whether all of the younger diabase dikes are of the same age.

MINERAL AGES

Rb and Sr analyses completed on various mineral phases from samples of the granite and of the metamorphic rocks are given in tables 3 and 4. Microcline was the major mineral analyzed, but all of the essential minerals were analyzed from three samples (GM-78, GM-98, and D1686). Mineral ages, calculated from the whole-rock-mineral isochrons are illustrated in figure 6. Internally consistent mineral ages were obtained on only two samples. GM-98, a tonalitic gneiss, is essentially composed of plagioclase, quartz, and biotite. Data for plagioclase, biotite, and the whole rock define a 2,440-m.y. isochron with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7067. D1686, the granite at Tincup Mountain, yields a plagioclase, total rock, biotite, muscovite isochron of 2,300 m.y. with an intercept of 0.7203. Microcline from this sample deviates from the mineral isochron beyond experimental error with a microcline-total-rock age of 2,080 m.y. Minerals from GM-78, a granitic gneiss, are highly discordant as shown in figure 6. Microcline-whole-rock ages of the remaining samples range from approximately 1,500 to 2,100 m.y. Conventional K-Ar ages (table 6) were obtained on biotites—1,570 m.y. (GM-56), 1,780 m.y. (D1686), and 2,310 m.y. (GM-98)—and on hornblende—2,680 m.y. (FCA-R-1).

All of these data show clearly that the Rb-Sr and K-Ar mineral systems have been disturbed at some time subsequent to the emplacement of the granite at 2,550 m.y. ago. Rosholt and others (1973) observed a remarkable colinearity of Pb isotope data obtained on microcline separates from the granitic rocks. They concluded that this secondary isochron resulted from uptake of radiogenic Pb by microcline from other phases in the granite as the consequence of a thermal event at 1,620±120 m.y. ago—the age defined by the microcline isochron. Had the Pb in the mineral systems totally equilibrated at this time, the appropriate whole-rock-microcline isochrons would have given this same age. Complete isotopic homogenization was not attained, however, and ages calculated from the whole-rock-microcline points are variable, but greater than 1,640 m.y. On the basis of regional variations in these ages, Rosholt and others (1973) suggested that the intensity of the thermal event increased from the western part of the Granite Mountains eastward to the Seminoe Mountains.

The mineral ages obtained in the present study support the interpretation of Rosholt and others (1973). Minerals from

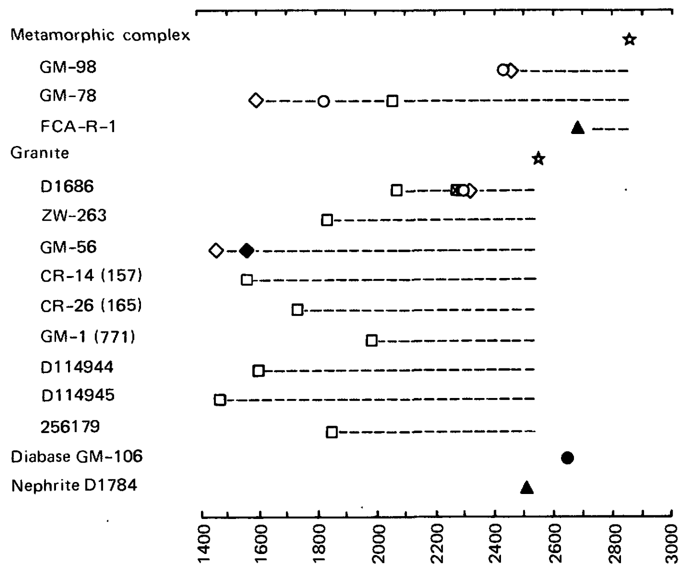


FIGURE 6.—Rb-Sr and K-Ar mineral ages. Rb-Sr mineral ages are calculated from the mineral-whole-rock line. Open symbols are Rb-Sr ages; stars, whole-rock isochrons; circles, plagioclase; squares, microcline; diamonds, biotite; square with cross, muscovite. Solid symbols are conventional K-Ar and $^{39}Ar/^{40}Ar$ ages: circle, labradorite; triangles, amphibole; diamond, biotite.

TABLE 5.—*Analytical data for $^{39}Ar/^{40}Ar$ ages*

[The $^{37}Ar/^{39}Ar$ value is corrected for ^{37}Ar decay using a half-life of 35.1 days. The percentages of $^{40}Ar_{rad}$, $^{36}Ar_{ca}$ and $^{39}Ar_{ca}$ are calculated using assumptions in Dalrymple and Lanphere (1971). The uncertainties on the ages are estimates of analytical precision at the 1σ level of confidence. Analytical techniques, methods of calculation, and the monitor mineral are described in Dalrymple and Lanphere (1971). Irradiations were made with a dose of approximately 4x10[18] nvt. Sample localities are: D1784, lat 42°33′40″ N., long 107°53′28″ W. GM-106-69, lat 42°34′10″ N.,long 107°48′34″ W.]

Sample	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	J[1]	Percent $^{40}Ar_{rad}$	Percent $^{36}Ar_{ca}$	Percent $^{39}Ar_{ca}$	Age (m.y.)
D1784 (nephrite).	235.3	322.1	0.1864	0.01122	87.6	47.1	20.4	2,460±45
Do	292.5	347.1	.4151	.01234	67.6	22.8	22.0	2,560±45
GM-106-69 (labradorite).	310.6	223.1	.2451	.01122	82.4	24.8	14.1	2,650±130

[1]J is a function of the age of the monitor and of the integrated fast neutron flux (Dalrymple and Lanphere, 1971).

TABLE 6.—*Conventional K-Ar ages*

[Analysts: R. F. Marvin, H. H. Mehnert, and Violet Merritt. $^{*40}Ar$ refers to radiogenic ^{40}Ar. The age uncertainty is given at the 2-σ level]

Sample	K_2O, percent	$^{*40}Ar$ (10^{-10} moles/gm)	$^{*40}Ar$ Percent	$^{*40}Ar/^{40}K$	Age (m.y.)
GM-56-68 (biotite).	8.36	301.2	99	0.1426	1,570±50
FCA-R-1 (hornblende).	.895	79.18	96	.350	2,680±160
D1686 (biotite).	5.40	236.1	99	.177	1,780±40
GM-98-68 (biotite).	8.99	604.7	99	.272	2,310±55

the westernmost sample (GM-98) give concordant ages of 2,440 m.y. Progressing eastwards, D1686 minerals are nearly concordant at 2,300 m.y. Minerals from GM-78 are strongly discordant with the lowest age of 1,600 m.y. recorded by biotite. Biotite from GM-56 is dated at 1,460 m.y. by Rb-Sr and 1,570 m.y. by K-Ar. Microcline from granitic rocks eastward to the Seminoe Mountains gives variably lowered ages that reach a lower limit of 1,500-1,600 m.y.

Some of the microcline separates analyzed by Rosholt and others (1973) and by NKomo and Rosholt (1972) were also analyzed in the present study. Two alternate comparisons of the results are given on figure 7. The $^{207}Pb/^{206}Pb$ age for each sample is calculated from the whole-rock and microcline tie line. Two Rb-Sr ages are given for each sample. The open circles (fig. 7) represent a comparison of microcline-whole-rock $^{207}Pb/^{206}Pb$ ages with the Rb-Sr ages as calculated from the appropriate whole-rock and microcline pairs. This follows conventional assumptions in the interpretation of Rb-Sr systematics of disturbed mineral systems (Lanphere and others, 1964). In effect, the Rb-Sr mineral isochron is assumed to rotate about the whole-rock point, and if the event is sufficiently strong to cause complete isotopic homogenization among the mineral phases, the resultant isochron will record the time of this disturbance. The solid circles (fig. 7) represent a comparison of microcline-whole-rock $^{207}Pb/^{206}Pb$ ages with the Rb-Sr ages as calculated on the basis of the microcline data points and the whole-rock isochron initial ratio of 0.7053. Brooks (1968) has documented a situation in which exchange of parent and daughter nuclides has occurred only between microcline and secondary alteration products of plagioclase. K-feldspar lost not only radiogenic ^{87}Sr but also significant amounts of Rb and common Sr. Thus, in crystalline rocks that have undergone a mild thermal metamorphism without recrystallization, moderate isotopic disturbances of microcline may not involve exchange of common Sr with that of the host reservoir, that is, the whole-rock system.

Regardless of the method used for calculating the microcline ages, the correlation of the Rb-Sr and $^{207}Pb/^{206}Pb$ ages as shown in figure 7 is reasonably good. The correlation is somewhat better if the Rb-Sr microcline ages

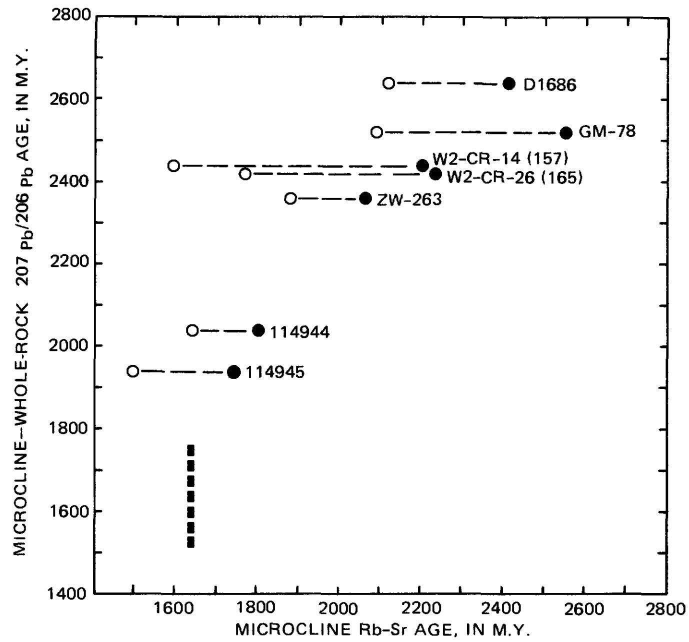


FIGURE 7.—Comparison of Rb-Sr and $^{207}Pb/^{206}Pb$ ages of microcline. Open circles, Rb-Sr ages calculated from microcline-whole rock isochrons. Closed circles, Rb-Sr microcline ages calculated from the microcline-whole-rock initial $^{87}Sr/^{86}Sr$ value. Vertical broken bar represents the 1,620±120-m.y. thermal event as defined by the Pb isotope data on microcline (Rosholt and others, 1973).

are computed on the basis of the isochron intercept. In both cases, with the exception of sample GM-78, the Pb-Pb ages are greater than the Rb-Sr ages. The general coherence of these ages is striking because resetting of the Rb-Sr microcline systems was accomplished by loss of radiogenic ^{87}Sr whereas the lead-isotope system records the disturbance by addition of radiogenic lead to the microcline. On the basis of a study in a contact metamorphic zone, Doe and Hart (1963) concluded that the lead-isotope system in feldspars was more easily affected than the Rb-Sr microcline and K-Ar hornblende systems but less easily than the K-Ar and Rb-Sr biotite systems.

The disturbance of mineral-age systems in rocks of the Granite Mountains is part of a regional pattern that is recognized in several areas of the Precambrian of Wyoming (Giletti and Gast, 1961; Hills and Armstrong, 1974; Reed and Zartman, 1973). The lowered mineral ages are generally interpreted as being the consequence of thermal events or episodes of metamorphism. Naylor, Steiger, and Wasserburg (1970) reported lowered Rb-Sr mineral ages in the southeastern Wind River Mountains and concluded that the rocks had been subjected to one or more events that occurred later than 2,000 m.y. ago. In this same area, biotites were dated at 2,200 and 1,430 m.y., whereas hornblende gave an older age of 2,620 m.y.—all by K-Ar (Bayley and others, 1973). Reed and Zartman (1973) concluded that rocks of the Teton Range had been affected by two thermal events—one about 1,800 m.y. ago and a second between 1,300 and 1,500 m.y. ago. Giletti and Gast (1961) also reported lowered mineral ages in the Teton and Gros Ventre Ranges, and Bassett and Giletti (1963) found similar lowered ages in the northwestern Wind River Mountains. Hills and Armstrong (1974) demonstrated the existence of a regional variation in K-Ar ages in Precambrian W rocks of the Laramie Range and of the Medicine Bow Mountains. They postulated the presence of a thermal or "geochronologic" front at the northernmost end of the Laramie Range, north of which micas yield 2,500 m.y. K-Ar ages, whereas micas from rocks of similar age farther south were lowered to between 1,400 and 1,600 m.y. Hills and Armstrong (1974) suggested that the front strikes southwestward from the northern Laramie Range towards the Seminoe Mountains.

The existence of such a front seems to be supported by our mineral data from the Granite Mountains, and it can be fairly well defined by considering both Rb-Sr and K-Ar biotite ages from the Laramie Range, the Granite Mountains, and the Wind River Mountains (fig. 8). The front appears to trend westerly from the northern Laramie Range, inasmuch as mineral ages in the Seminoe Mountains and in all but the northwestern part of the Granite Mountains have been lowered. It can be projected farther west into the Wind River Mountains, where biotite ages are systematically lowered from north to south at the southeastern end of the range (fig. 8). The biotite that gives the 1,420-m.y. K-Ar age in the southeastern Wind River Mountains was obtained from a mylonitized granite (Bayley and others, 1973), and possibly the age dates the movement of a major shear zone. West of this locality, on the southern flank of the range, biotite from a basement core is dated at 1,840 m.y., whereas a whole-rock Rb-Sr determination clearly establishes the age as Precambrian W (Goldich and others, 1966).

The consistent lowering of K-Ar and Rb-Sr biotite ages in rocks of Precambrian W age in the region south of the front (fig. 8) is an impressive feature. Geologic evidence that might support the presence of a metamorphic event is lacking except in proximity to the major terrane of Precambrian X and Y rocks in southern Wyoming and Colorado. An alternative interpretation to that of a discrete metamorphic event is that the reset mineral ages reflect crustal uplift and cooling below temperatures at which the radiometric systems in the minerals attain closure or cease to diffuse daughter products (Armstrong, 1966; Wetherill, 1966; Harper, 1967). This interpretation would require differential uplift of large crustal blocks in late Precambrian X or early Precambrian Y time, with the obvious possibility of one or more second-order events or cooling episodes superimposed on the uplifted blocks, which would account for some of the variability in mineral ages as presently observed.

At the northern end of the Laramie Range, in the northwestern part of the Granite Mountains and in the southeastern part of the Wind River Mountains, the gradient in Rb-Sr and K-Ar biotite ages is steep—ages are drastically lowered over distances of 10-20 km. These steep age gradients are more likely to have resulted from one or more zones of major vertical dislocation than from a thermal or metamorphic event somehow related to younger Precambrian orogenesis some 100-150 km to the south. A series of westerly trending faults is present in Phanerozoic rocks (Bayley and Muehlberger, 1968); these roughly coincide with or parallel the front defined by the biotite ages (fig. 8). Some or all of these may well have had precursors in the Precambrian. In the Granite Mountains, this hypothetical fault zone would lie near sample D1686 (fig. 2). Although a fault was not mapped, the existence of one is not precluded by our field study, as rocks with strongly developed vertical foliation occur near this locality. In the southeastern Wind River Mountains, several large Precambrian faults are mapped (Bayley and others, 1973) and, as mentioned previously, the K-Ar age of 1,420 m.y. is on biotite from a mylonitized granite apparently associated with one of the fault zones.

If the lowered mineral ages in Precambrian W rocks south of the front (fig. 8) are indeed the result of cooling as a consequence of regional uplift, estimates of temperatures and depths at which the presently exposed rocks resided prior to this uplift can be made. Biotite loses radiogenic Ar and Sr at temperatures in excess of about 300°C (Hanson and Gast, 1967; Hanson, 1971). Using estimates of average geothermal gradients that might have existed approximately 1,500 m.y. ago (Hargraves, 1976), presently exposed Precambrian W rocks with lowered biotite ages would have been uplifted from depths of 11-13 km between 1,400 and 1,600 m.y. ago. Local survival of amphibole ages such as of the nephrite in the Granite Mountains (table 5), and of hornblende in the Wind River Mountains from the same locality as the 2,210 m.y. biotite age (Bayley and others, 1973), suggests temperatures of less than 500°C (Steiger and others, 1976) and depths of less than 18-22 km in the northern part of the block. K-Ar hornblende ages of 1,690 to 1,820 m.y. from Precambrian W rocks of the central Laramie Range (Hills and Armstrong, 1974) suggest that these rocks cooled below about 500°C at this time and subsequently below 300°C between 1,400 and 1,600 m.y. ago, as indicated by the biotite ages. The depth calculations are not meant to be highly precise; they have large uncertainties because of the known variability of present-day geothermal gradients from one geologic province to another (Roy and others, 1968) and imprecise knowledge of the blocking temperature and diffusion characteristics of biotite. The actual geothermal gradients may in fact have been greater than average because of the high radioelement content of some of the constituent rocks such as in the Granite Mountains (Rosholt and others, 1973), and, more than likely, the depth estimates are maximum values.

In spite of these uncertainties, the temperature and depth

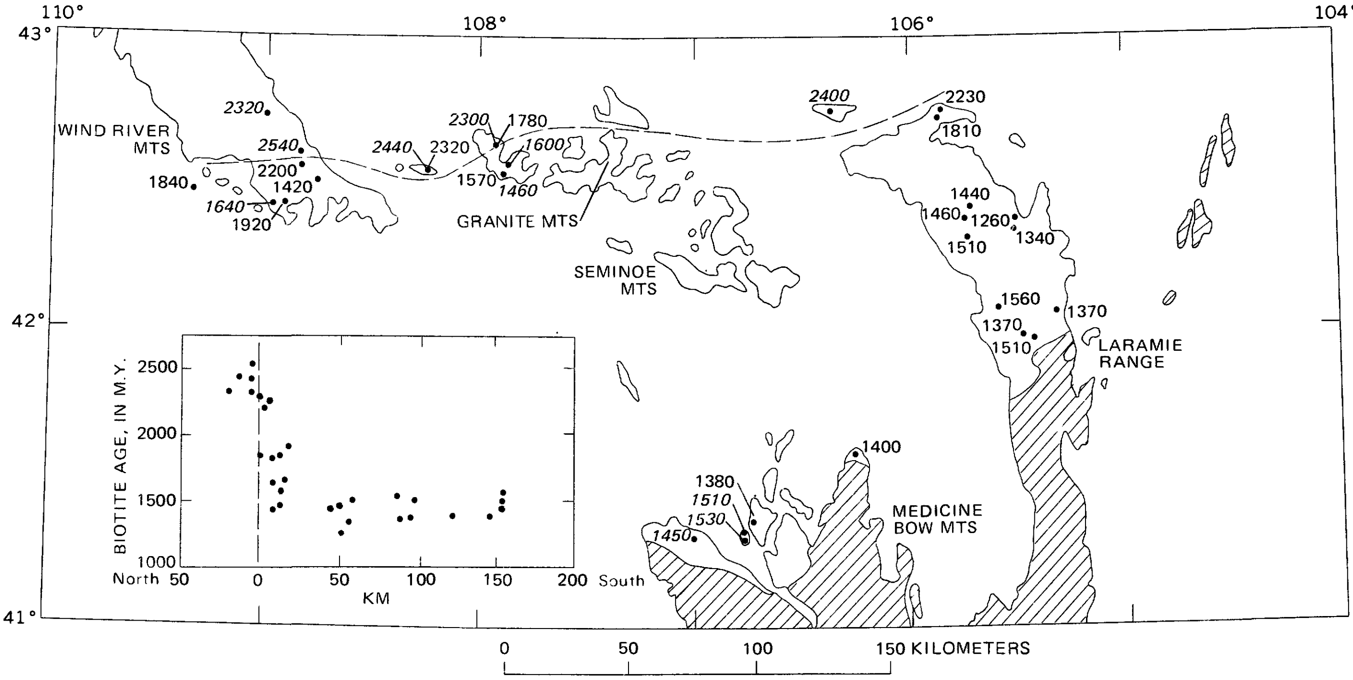


FIGURE 8.—K-Ar and Rb-Sr ages, in millions of years, of biotite from Precambrian W granitic and metamorphic rocks of southern Wyoming. Rb-Sr ages are italicized. Patterned areas are underlain by Precambrian X and Y rocks, here undifferentiated. The east-west-trending—line marks the front that separates biotite ages of 2,300 m.y. and older from those of 2,230 m.y. and younger. The inset shows ages plotted as a function of north or south distance from the dashed line. Data are from this study, Giletti and Gast (1961), Goldich and others (1966), Hills and others (1968), Naylor, Steiger, and Wasserburg (1970), Bayley, Proctor, and Condie (1973), Hills and Armstrong (1974), and Divis (1976), and M. A. Lanphere (written commun., 1977). Precambrian outlines from Bayley and Muehlberger (1968).

(pressure) parameters suggested by the mineral ages correspond to conditions of "very low grade" to "low grade" metamorphism as defined by Winkler (1974). Thus, the lack of definitive geologic evidence for a thermal event is not surprising, although pervasive chloritization of biotite, saussuritization of plagioclase, and protoclastic textures in the granite of Lankin Dome (table 2) could be the result of the granite having been held at these metamorphic conditions for some 1,000 to 1,200 m.y. after crystallization.

If the foregoing interpretation has any basis in fact, the uplift of a large block of Precambrian W rocks in late Precambrian X or early Precambrian Y time has important implications to the regional tectonics of the area. Several kilometers, perhaps 10 km or more, of material would had to have been removed by erosion subsequent to or concomitant with the uplift. In Precambrian Y time, large sedimentary basins to the northwest, west, and southwest of southern Wyoming received voluminous amounts of sediments that formed the Belt Supergroup and correlative rocks (Stewart, 1976). The Uinta Mountain Group would be a particularly attractive repository for material eroded from the uplifted block, and the source of the Uinta Mountain Group is thought to be toward the north (Hansen, 1965; Crittenden and Wallace, 1973).

CONCLUSIONS

Reconnaissance mapping of the western end of the Granite Mountains in central Wyoming has identified a metamorphic complex composed mainly of a layered sequence of quartzofeldspathic gneisses, amphibolites, and schists. Metagraywacke and amphibolite form sizable units at the westernmost end of the Granite Mountains. Tonalitic to granodioritic gneisses interlayered with lesser amounts of amphibolite, biotite schist, serpentinite, augen gneiss, and epidote gneiss form a sizable portion of the exposed metamorphic complex. The gneisses are well banded and range from layers of relatively uniform composition to migmatitic varieties. Interlayers of amphibolite are locally broken and distended to form boudins and rotated blocks within the gneisses.

Rocks of the metamorphic complex are at amphibolite grade and were probably derived from a sequence of interlayered mafic volcanic rocks and graywackes or silicic volcanic rocks. The sequence may be correlative with or compositionally analogous to the greenstone-graywacke terrane exposed in the southeastern Wind River Mountains. Here, Bayley, Proctor, and Condie (1973) have described a thick section of graywacke, greenstone, and iron-formation.

A migmatitic complex containing amphibolites and serpentinites is suggested to be the remnant of a mafic volcanic basement on which the sedimentary-volcanic sequence was deposited.

Compositional banding and foliation within the metamorphic complex commonly dip southeast and south toward the younger granite batholith. Other than compositional banding, primary structures in the metamorphic complex have been obliterated by metamorphism.

The metamorphic complex was intruded by a batholith and two satellite bodies of biotite granite. The granite is medium to coarse grained, generally massive but locally foliated near the margin and in the satellite bodies, and is cut by late-stage dikes of granite, aplite, and pegmatite. Rocks of the metamorphic complex are also pervasively intruded by these late-stage dikes especially in proximity to the main bodies of granite.

As a result of well-developed exfoliation, the granite typically forms rounded hills and knobs. In most areas, weathering has affected the granite to depths of several tens of meters or more and surface samples are characteristically stained with iron oxides. Strongly altered zones, generally linear and steeply dipping, occur within the granite; they contrast sharply with unaltered phases by virtue of a well-developed blocky fracturing and a greater resistance to weathering. The alteration has been allochemical in that substantial amounts of epidote have been introduced, biotite has been partially to completely converted to chlorite and granular sphene, and microcline has been removed. In some of these alteration zones, the granite has been intensely silicified (Stuckless and others, 1977). Similar alteration occurs in the metamorphic complex where these zones are commonly associated with the nephrite mineralization.

Numerous diabase dikes with a dominant east-northeast trend intrude both the granite and the metamorphic complex. These dikes range in thickness from several meters to several tens of meters. They are chilled against the enclosing rocks and generally coarser in grain size toward the centers. The dikes show variable degrees of alteration (Sherer, 1969), although some are remarkably fresh; olivine, pyroxene, and labradorite are their essential minerals. It is not known whether more than one age of dikes is present. Within the metamorphic complex, some of the amphibolite bodies are discordant with the compositional banding; these are presumably metamorphosed mafic intrusions. The discordant amphibolites, however, are clearly distinguishable from the younger diabase dikes.

Veins of nephrite (jade) occur within the metamorphic complex, mainly at the western end of the area. These are of local economic interest and are mined on a small scale. The nephrite veins were not studied in detail, and the reader is referred to Sherer (1969) for a comprehensive account of these deposits.

Geochronologic studies have established a time framework into which the major Precambrian events of the Granite Mountains can be placed. An Rb-Sr isochron obtained on whole-rock samples of gneisses gives an age of 2,860±80 m.y. This age is interpreted as the time at which the rocks of the metamorphic complex attained amphibolite-grade metamorphism. An initial $^{87}Sr/^{86}Sr$ of 0.7048±0.0012 is unusually high for juvenile material at 2,900 m.y. ago and suggests that the Sr in the protoliths of the metamorphic complex had a significant pre-metamorphic crustal history. Estimations based upon this initial Sr ratio, the metamorphic age of 2,860 m.y., and the average Rb/Sr ratio of the gneisses suggest that the Sr may have separated from the mantle some 300 to 400 m.y. before metamorphism. Geologically this implies that the rocks themselves or the source terrane from which they were derived may be that old. Data obtained on four samples of amphibolite and massive tonalitic gneisses fall below the main isochron defined by the quartzofeldspathic gneisses and indicate an initial Sr ratio of approximately 0.7017. The amphibolites, at least, are likely to have been of volcanic origin; the lower initial Sr ratio would favor an interpretation that the layered quartzofeldspathic gneisses are partly or completely sedimentary in origin.

Twenty samples of granitic rock from the immediate area of study and from adjacent areas were analyzed for Rb and Sr. In general, data obtained from surface samples and on cores from shallow drill holes show excessive scatter on an isochron plot. Data for seven samples from deep drill holes define an isochron of 2,550±60 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7053±0.0056. This age is interpreted as dating the time of emplacement of the main body of granite in the Granite Mountains. Samples from other granite bodies in adjacent areas north of the map area and in the Seminoe Mountains provide data that plot on or close to the isochron, suggesting, at least provisionally, that these granites are approximately the same age. The Rb-Sr isochron age is in agreement with U-Pb data obtained on a zircon from the granite of Tincup Mountain and with zircon ages by K. R. Ludwig and J. S. Stuckless (written commun., 1976) on the main body.

A sample of nephrite and one of labradorite from a fresh diabase yielded $^{39}Ar/^{40}Ar$ ages of 2,510±35 and 2,650±130 m.y. respectively. These data suggest that the diabase dikes were emplaced and the nephrite veins were formed only shortly after the granite was intruded. Ratios for $^{87}Sr/^{86}Sr$ determined on epidote and on a whole-rock sample from an epidotized zone in the granite also suggest that this alteration occurred within a few tens of millions of years after the granite was emplaced. Similar alteration in gneisses adjacent to nephrite mineralization, and the age of the nephrite, support this interpretation.

Rb-Sr and K-Ar ages of feldspars and micas from both the metamorphic complex and from the granite have been lowered to varying degrees. Within the western part of the Granite Mountains, mineral ages are increasingly lowered from west to east. This pattern in Rb-Sr and K-Ar ages is consistent with that observed earlier by Rosholt and others (1973) from the Pb-isotope systematics in microclines from the granite.

When the mineral ages, especially Rb-Sr and K-Ar biotite ages, of the Granite Mountains are considered in a regional context with those from the Laramie Range and from the Wind River Mountains, a regional pattern emerges that can best be explained by major vertical tectonics in late Precambrian X or early Precambrian Y time. A biotite-age discontinuity in Precambrian W rocks extends from the north end of the Laramie Range, through the Granite Mountains, to the southeast end of the Wind River Mountains. North of this discontinuity, biotite ages are 2,300 m.y. or greater, whereas ages to the south decrease rapidly to between 1,400 and 1,600 m.y. This pattern could have been generated by vertical uplift of the southern block, south of the age discontinuity, between 1,400 and 1,600 m.y. ago. In this interpretation, the biotite ages register the time at which rocks at the presently exposed surface were uplifted and cooled through the 300°C isotherm. An uplift of several kilometers is required, with the corollary that several kilometers were removed by erosion at this time. This postulated uplift could have supplied detritus to the dominantly Precambrian Y Uinta Mountain Group.

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