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GEOLOGY AND GEOCHEMISTRY OF PROTEROZOIC GRANITIC AND MAFIC ROCKS IN THE REDROCK AREA, NORTHERN BURRO MOUNTAINS, GRANT COUNTY, NEW MEXICO—A PROGRESS REPORT

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Abstract—A complex Proterozoic terrain in the northern Burro Mountains consists of metamorphic rocks (Bullard Peak and Ash Creek Series, 1550–1570 Ma, U/Pb) that are intruded by granitic and mafic rocks. The granitic rocks include (1) Burro Mountain granite (oldest, ~1445 Ma, U/Pb), (2) gneissic granite/granodiorite (~1380 Ma, K/Ar), (3) Jack Creek rapakivi granite (1220.9 ± 3.5, 1198 ± 4.7 Ma, $^{40}Ar/^{39}Ar$), (4) Redrock granite (1210 ±5, 1204.8 ± 12 Ma, $^{40}Ar/^{39}Ar$; 1328 ± 58 Ma Sm/Nd isochron), (5) fine-grained alkali-feldspar and biotite granite dikes, (6) rhyodacite/dacite porphyry dikes, and (7) pegmatite dikes (youngest). The Redrock granite consists of four textural and compositionally distinct phases (biotite-hornblende, hornblende, K-feldspar, and miarolitic biotite granites). Approximately 50 small anorthosite xenoliths (1216.9 ± 5.3, 1228.5 ± 4.5 Ma, $^{40}Ar/^{39}Ar$; 1326 ± 830 Ma, Sm/Nd isochron) are scattered in a northeast-trending zone throughout the miarolitic biotite granite. K-rich minette (1420.5 ± 4.5 Ma, $^{40}Ar/^{39}Ar$; 1135 ± 71 Ma, Sm/Nd isochron) occurs as coeval isolated enclaves, swarms of enclaves, and synplutonic dikes within the Jack Creek rapakivi granite. Diabase/gabbro/diorite stocks and dikes intruded the metamorphic and granitic rocks. The age relationships of the granites and minettes remain unclear and will hopefully be resolved by additional U/Pb dating of zircons. The number of $^{40}Ar/^{39}Ar$ age dates clustering about 1200 Ma strongly suggests that a heating event or uplift occurred at that time. Geochemical and isotopic data indicate that the Redrock granite, anorthosites, Jack Creek rapakivi granite, Burro Mountain granite, and metamorphic rocks were derived from different protoliths. The anorthosites and diabase probably tapped a moderately depleted mantle source. The Jack Creek rapakivi granite was presumably derived from a source characterized by subtle, long-term LREE enrichment, whereas that of the Redrock granite pluton was slightly depleted. Both were clearly more juvenile (Nd model ages ~1600 Ma) in nature than the metamorphic rocks of the region (Nd model ages ~1900 Ma) and may include a significant Middle Proterozoic mafic lower crust/subbcontinental lithospheric mantle component. The metamorphic rocks of the region register an older signature than what has been considered typical of the Nd province 3 of the western United States.

INTRODUCTION

The Burro Mountains offer an excellent opportunity to examine the relationships of anorthosite, minette (a type of lamprophyre), and granitic rocks and will ultimately provide a better understanding of the petrogenesis of these rocks and the tectonic evolution of the Proterozoic crust, especially of southern Laurentia. The purpose of this preliminary report is to describe the lithology and chemistry of the various Proterozoic rocks in the northern Burro Mountains. This report is only a progress report of on-going studies; future papers will describe the petrogenesis and tectonic setting in more detail.

The Redrock area in the northern Burro Mountains in southwestern New Mexico (Fig. 1) comprises a complex Proterozoic terrain consisting of metamorphic rocks (Bullard Peak and Ash Creek Series) intruded by granitic and mafic rocks (Hewitt, 1959; Hedlund, 1980a, b; McLemore and McKee, 1988a). The granitic rocks include (1) Burro Mountain granite (oldest), (2) gneissic granite/granodiorite, (3) Jack Creek rapakivi granite, (4) Redrock granite, (5) fine-grained alkali-feldspar and biotite granite dikes, (6) rhyodacite/dacite porphyry dikes, and (7) pegmatite dikes (youngest). In addition, approximately 50 small anorthosite xenoliths are scattered in a northeast-trending zone throughout the miarolitic biotite granite phase of the Redrock granite near and on the Redrock Wildlife Refuge (Hewitt, 1959; Hedlund, 1980a). No other Proterozoic anorthosite occurrences have been reported from New Mexico and they are rare in the United States.

The Jack Creek rapakivi granite is spatially associated with the Redrock granite containing the anorthosite xenoliths. Rapakivi is Finnish for rotten or crumbly rock and describes the tendency of the rapakivi granite to weather easily. The rapakivi texture refers to the mantling of K-feldspar phenocrysts by plagioclase (Haapala and Rämö, 1990). Most rapakivi granites are Middle–Early Proterozoic, although rapakivi textures have been described from some Phanerozoic and Archean granites (Haapala et al., 1995; Murakami and Imaoka, 1985; Sibiya, 1988). The rapakivi granites are currently the focus of active worldwide research that pursues such items as the source of the rapakivi magma, the genetic relationships between the granite and penecontemporaneous mafic rocks, the origin of the rapakivi texture,

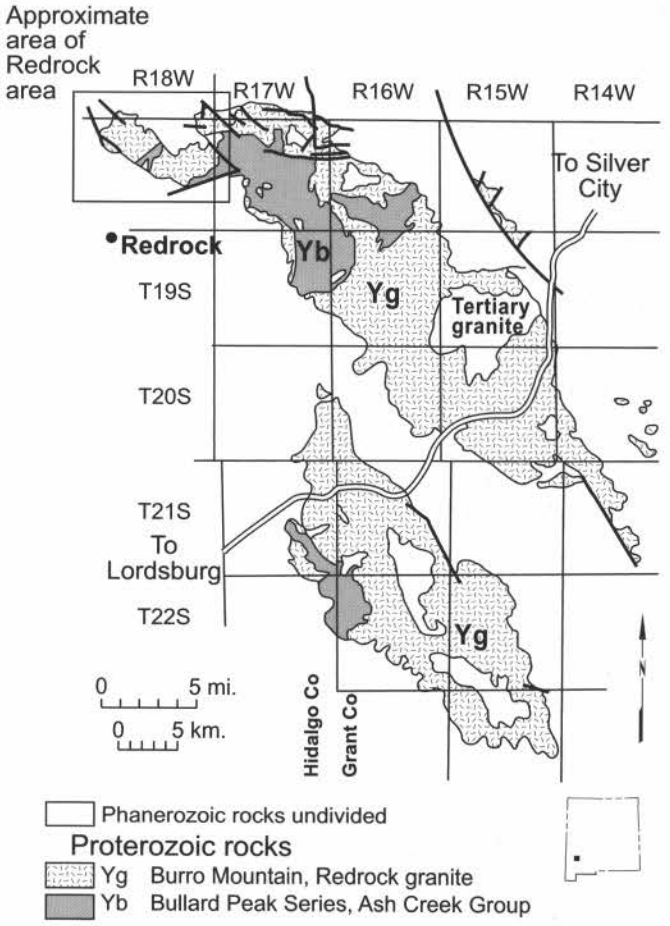


FIGURE 1. Generalized geologic map of the Proterozoic rocks in the Burro Mountains. Geology compiled from Drewes et al. (1985).

and the tectonic setting of these rocks (Rämö and Haapala, 1995). In Fennoscandia, for instance, there is good petrologic and geophysical evidence that the rapakivi granites were generated in an intracontinental extensional environment by crustal remelting caused by mafic underplating (Haapala and Rämö, 1992).

Enclaves and synplutonic dikes of minette are associated with the Jack Creek rapakivi granite. The petrologic relationship and temporal association between the rapakivi granite and minette remains unknown. Spatial and temporal association of rapakivi granite and minette is rare in the world.

METHODS OF STUDY

This study began in 1987, when a preliminary investigation of the Proterozoic rocks was undertaken in order to assess their economic potential (McLemore and McKee, 1988a). This early investigation also indicated that previous mapping by Hewitt (1959) and Hedlund (1980a, b) did not adequately differentiate the diverse Proterozoic rocks. Subsequent mapping by Finnell (1987) grouped the Proterozoic rocks together as one unit. Additional studies by the authors continued in 1988, 1996, and 1998–2000 and are ongoing (McLemore et al., 1999b; Kosunen et al., 1999; Rämö et al., 1999).

Current studies by the authors include detailed mapping and sampling of the Proterozoic rocks in order to explain the petrogenesis of the anorthosites and spatially related granites and minettes, and to assess their economic potential. Approximately 77 km^2 are being mapped at a scale of 1:12,000 and transferred to a map scale of 1:24,000 using standard U.S. Geological Survey (USGS) 7½-minute topographic quadrangle maps (Redrock, Brushy Mountain, Mangas Springs, Bullard Peak). Only the western portion of the mapped area is shown in Figure 2; see McLemore (this volume, p. 246, fig. 2) for a map of the eastern portion of the area.

Samples of the igneous rocks were collected and analyzed by X-ray fluorescence spectrometry (XRF) for major and trace elements to distinguish between the various lithologies and to determine the magmatic differentiation history. Major elements were analyzed by XRF on fused glass discs and trace elements using pressed-powder briquettes. Instrumental neutron-activation analyses on many of the samples were determined commercially by XRAL. Samples were also submitted to the New Mexico Geochronological Research Laboratory at New Mexico Bureau of Mines and Mineral Resources (NMBMMR) for age determinations by $^{40}Ar/^{39}Ar$ methods; laboratory procedures are briefly described by McLemore et al. (1999a) or can be obtained from the senior author. Representative samples also have been analyzed for Sm, Nd, Rb, and Sr isotopes at the Geological Survey of Finland by the second author; analytical methods are described in Rämö and Calzia (1998). The geochemical and isotopic data will be presented in future reports and are only summarized here.

REGIONAL GEOLOGIC SETTING

The Burro Mountains lie in the Mexican Highland section of the Basin-and-Range physiographic province in southwestern New Mexico. The regional structural evolution of the southwestern United

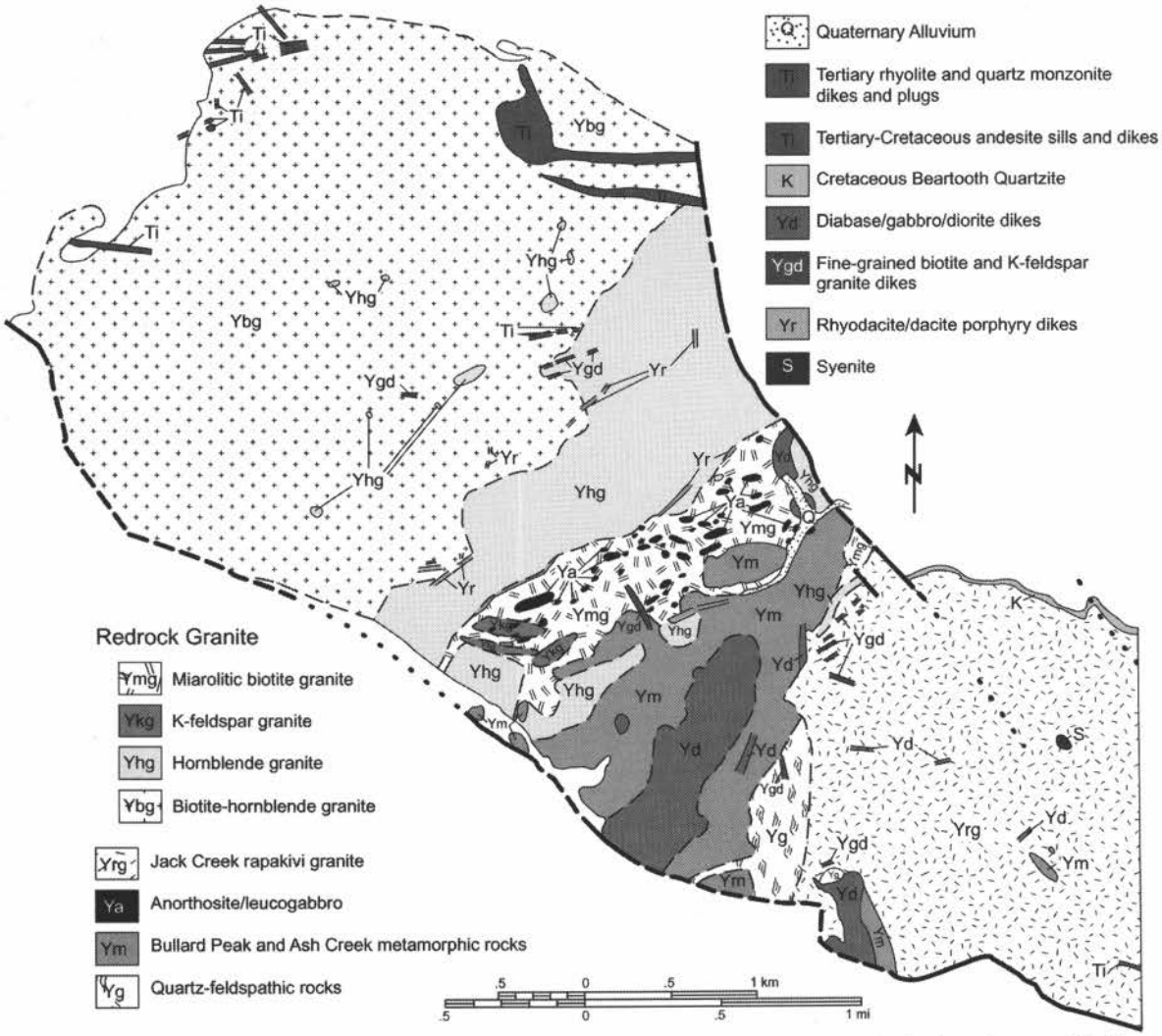


FIGURE 2. Generalized geologic map of the Proterozoic rocks in the Redrock area, northern Burro Mountains (mapping by the authors, modified in part from Hewitt, 1959; Hedlund, 1980a, b; Finnell, 1987).

States and northern Mexico, specifically the Burro Mountains, has been dominated by a succession of dynamic and sometimes rapidly changing plate tectonic settings from the Proterozoic to the Recent (Coney, 1978; Karlstrom and Bowring, 1988; Karlstrom et al., 1990). This prolonged history of complex continental tectonics can be divided into nine phases: (1) Mazatzal orogeny, 1650–1600 Ma (Karlstrom and Bowring, 1988; Karlstrom et al., 1990). (2) Late Proterozoic granitic plutonism, 1450–1400 Ma (Stacey and Hedlund, 1983; Karlstrom and Bowring, 1988; Karlstrom et al., 1997). (3) 1100–1200 Ma period of mafic, volcanic, and A-type granitic intrusions in Texas and Arizona, coincident with the Grenville orogeny (Mosher, 1998; Reese et al., 2000). (4) Paleozoic period of alkaline and carbonatite magmatism (McLemore et al., 1999a; McMillan et al., this volume). (5) Paleozoic period of basin formation and uplift as part of the ancestral Rocky Mountains (Florida uplift, Pedregosa basin, Ross and Ross, 1986). (6) Cretaceous continental arc, shallow marine deposition (Drewes, 1991). (7) Laramide compressional deformation and magmatic arc volcanism and plutonism (Late Cretaceous–early Tertiary, Drewes, 1991). (8) mid-Tertiary calc-alkaline volcanism to bimodal volcanism with caldera formation (Schoolhouse Mountain caldera related to the Datil-Moggolon field, McIntosh et al., 1991). (9) late Tertiary–Quaternary Basin-and-Range extensional deformation (Coney, 1978). Each of these tectonic periods left remnant structural trends that were either reactivated or crosscut by younger tectonic events and together have resulted in a structurally complex, relatively thin, brittle and anisotropic crust.

The Proterozoic rocks in the Redrock area in the northern Burro Mountains lie along the southern ring fracture zone of the Schoolhouse Mountain caldera. The 33.5-Ma Schoolhouse Mountain caldera (McIntosh et al., 1991) is interpreted to be asymmetrical, as much as 1.5 km deep, and filled with the tuff of Cherokee Canyon and Box Canyon (Finnell, 1987; Schoolhouse Mountain Formation of Wahl, 1980). Younger north- and northwest-striking Basin-and-Range faults have offset the caldera boundary (Finnell, 1987). Only the Proterozoic rocks are discussed in this report, but they have been cut and altered by these younger tectonic events.

DESCRIPTION OF PROTEROZOIC ROCKS

Bullard Peak and Ash Creek metamorphic rocks

The oldest rocks in the Redrock area (Table 1; Fig. 2) are the metamorphic Bullard Peak and Ash Creek Series (Hewitt, 1959) that were later correlated to each other by Hedlund (1980a, b). The metamorphic rocks were not studied in detail for this study and the reader is referred to Hewitt (1959) for more information. Individual units are irregular in shape, discontinuous, and difficult to map. Therefore, they are typically grouped as undifferentiated metamorphic rocks (Hedlund, 1980a, b; Finnell, 1987; unpublished mapping by the authors).

The metamorphic rocks consist of a variety of light-colored quartz-feldspathic gneisses and schists, dark-colored biotite and hornblende schists, black amphibolite, gray to greenish-gray phyllite, gray to white quartzite, and banded green, white, and yellow serpentine-carbonate rocks (Hewitt, 1959). Metamorphic foliation is well to poorly developed and variable in orientation. The metamorphic rocks consist of interlayered metaigneous and metasedimentary units and are disrupted by intrusion of granites, fine-grained biotite granite dikes, and pegmatites. Migmatites are common along some contacts with the younger granitic intrusions; other contacts with the younger Jack Creek rapakivi granite are sharp. Locally in the Smith Mountain area, small pods of hornfels and skarn occur where the granite has intruded the serpentine-carbonate rocks.

Burro Mountain granite

Although the Burro Mountain granite (granite of Burro Mountain, Hedlund, 1980a, b) is not exposed in the mapped area, it was examined and sampled from outcrops south of the mapped area, along the Redrock Road and US-90. It is pinkish-gray and black, medium grained, granular to foliated, and contains quartz, microcline, plagioclase, biotite, and varying amounts of zircon, muscovite, magnetite, epidote, iron oxides and locally pyrite. Small xenoliths (<1 m in diameter) of metamorphic rocks are locally found. A U/Pb date of 1445 ± 10 Ma was reported on a sample by Hedlund (1980b).

Gneissic granite/granodiorite

The gneissic granite/granodiorite is gray, medium- to coarse-grained, hypidiomorphic-granular to porphyritic granite to granodiorite that consists of microcline, oligoclase, quartz, biotite, hornblende, and trace amounts of titanite, zircon, apatite, epidote, and magnetite. The unit is typically foliated and contains xenoliths of metamorphic rocks. The origin of the foliation is not known (i.e., metamorphic versus igneous). It is exposed in the eastern part of the mapped area, south and east of Wild Horse Mesa (McLemore, this volume, p. 245). In Wild Horse Canyon, the gneissic granite/granodiorite is in contact with foliated Jack Creek rapakivi granite. Igneous foliation of the rapakivi granite near the contact suggests that the gneissic granite/granodiorite is older. Intrusive contacts with the Burro Mountain granite are not exposed, therefore, the age relationship to the Burro Mountain granite is uncertain. A U/Pb date of 1380 ± 45 Ma was reported on a sample by Hedlund (1980b).

TABLE 1. Age relationships of the Proterozoic and younger rocks in the northern Burro Mountains.

Units
Volcanic-epithermal veins
Tertiary rhyolite and quartz monzonite dikes and plugs
Tertiary–Cretaceous andesite sills and dikes
Cretaceous Beartooth Quartzite
Proterozoic rocks
Diabase/gabbro/diorite dikes
Pegmatites dikes
Serpentinite veins
Fine-grained biotite and K-feldspar granite dikes (1206 ± 15 Ma, $^{40}Ar/^{39}Ar$)
hyodacite-dacite porphyry dikes
Redrock granite (1328 ± 58 Ma Sm/Nd isochron)
Miarolitic biotite granite
K-feldspar granite
Hornblende granite (1210 ± 5, 1204.8 ± 12 Ma, $^{40}Ar/^{39}Ar$)
Biotite-hornblende granite
Jack Creek rapakivi granite (1220.9 ± 3.5, 1198.0 ± 4.7 Ma, $^{40}Ar/^{39}Ar$)
Minette (1420.5 ± 4.5 Ma, $^{40}Ar/^{39}Ar$; 1135 ± 71 Ma Sm/Nd isochron)
Anorthosite/leucogabbro (1216.9±5.3, 1228.5 ± 4.5 Ma, $^{40}Ar/^{39}Ar$; 1326 ± 830 Ma Sm/Nd isochron)
Diabase/diorite/gabbro (1500–1535 Ma, U/Pb, Stacey and Hedlund, 1983; but the dike intruded the 1445 Ma Burro Mountains granite)
Gneissic granite/granodiorite (1380 ± 45 Ma, K/Ar, Hedlund, 1980b) (Ygd of Hedlund)
Burro Mountain granite (1169 ±11 Ma, $^{40}Ar/^{39}Ar$; correlated to 1445 ± 10 Ma U/Pb by Hedlund, 1980b) (Yg of Hedlund, 1980a, b)
Bullard Peak and Ash Creek Metamorphic rocks (1550–1570 Ma, U/Pb, Stacey and Hedlund, 1983)
Quartz-feldspathic gneiss (1202.3 ± 2.4 Ma, $^{40}Ar/^{39}Ar$) (granulite of Hedlund, 1980a)

Diabase/gabbro/diorite

The mafic intrusive rocks range in composition from diabase to gabbro to diorite and crop out as black to dark gray, fine- to medium-grained stocks and dikes that consist of hornblende and/or pyroxene, plagioclase, biotite, magnetite, and rare pyrite, calcite and quartz. Locally, the mafic rocks are foliated; elsewhere they are uniform in texture. The largest intrusion, west and south of Lydian Peak, is a large dike or small stock (Fig. 2). Most diabase intrusions occur as dikes a few meters wide and as much as several hundred meters long. Small bodies brecciate or grade into the anorthosite/leucogabbro xenoliths. Mafic dikes intruded all of the granitic and metamorphic rocks. These field relationships imply that there may have been two or more periods of mafic magmatism, pre-granitic, post-granitic, or both.

Anorthosite/leucogabbro

Approximately 50 anorthosite/leucogabbro xenoliths are scattered throughout a northeast-trending zone in the miarolitic biotite granite phase of the Redrock granite. The largest body is approximately 270 m long and 30 m wide. The anorthosite is heterogeneous and commonly brecciated by diabase, gabbro, and miarolitic biotite granite. The anorthosites are tan to white-gray and black, fine–coarse grained with small patches of white leucogabbro. Euhedral plagioclase crystals vary in size from a few centimeters to 15 cm long (McLemore et al., this volume, p. 48, fig. S.1.6). In thin section, the anorthosite has a texture ranging from hypidiomorphic-granular to diabasic to pegmatitic. It consists of unzoned plagioclase with hornblende or pyroxene and chlorite, biotite, magnetite-ilmenite, and rare titanite, apatite, pyrite, olivine, and zircon. K-feldspar and quartz xenocrysts occur locally along the edges of the anorthosite/leucogabbro bodies and are probably derived from granitic rocks. Fine-grained biotite granite dikes cut and brecciate the anorthosite and miarolitic biotite granite in places. McLemore and McKee (1988a) described a quartz anorthosite and hybrid anorthosite, which are now interpreted as anorthosite that was brecciated and migmatized by granite.

Jack Creek rapakivi granite

The Jack Creek rapakivi granite is pink-gray to red-orange and medium–coarse grained. It is characterized by large K-feldspar phenocrysts, some of which are mantled by plagioclase forming the rapakivi texture. The granite consists of plagioclase, K-feldspar, quartz, biotite, and accessory apatite and magnetite. The granite is exposed from Lydian Peak, north of Redrock, eastward to the Schoolhouse Mountain fault, east of Wild Horse Mesa (Fig. 2; McLemore, this volume, p. 245). It is named in this study after Jack Creek, which cuts through the granite east of Lydian Peak. Hedlund (1980a) originally designated it as part of the granite of Redrock, but this granite is texturally, mineralogically, and chemically distinct from the Redrock granite that is exposed west and north of Lydian Peak. Field relationships, discussed below, suggest that the Jack Creek rapakivi granite is older than the hornblende granite phase of the Redrock granite. The rapakivi granite is locally foliated near the contact with the older gneissic granite/granodiorite in Wild Horse Canyon.

Numerous xenoliths of older metamorphic rocks and penecontemporaneous enclaves and synplutonic dikes of minette characterize the Jack Creek rapakivi granite. Xenoliths are extraneous pieces of older country rock introduced into the magma, whereas enclaves are residues of melting or coeval magma (Didier and Barbarin, 1991). Xenoliths within the rapakivi granite range in size from a few centimeters in diameter to lenses tens of meters across. Typically, the metamorphic xenoliths are similar to the metamorphic rocks found in the Bullard Peak Series and consist predominantly of light-colored, fine-grained quartz-feldspathic gneisses and schists, although locally, dark-colored biotite schists and amphibolites are common. Foliation of the larger individual xenoliths in most areas is randomly oriented, indicating rotation of the blocks during granitic intrusion.

Three outcrops of brick-red, metasomatic syenite plugs occur in rapakivi granite along Jack Creek, west of Jack Creek, and at Ramsey Saddle in the Wild Horse Mesa area. The metasomatic syenite consists of K-feldspar, biotite, and plagioclase; quartz is absent. The syenite exhibits similar coarse-grained texture as the enclosing rapakivi granite. The syenites contain 8.4–13.4% K_2O and 0.1–0.3% Na_2O (McLemore et al., this volume, p. 45), and are grossly similar in composition and occurrence to metasomatic syenites that are characteristic of Cambro–Ordovician alkaline magmatism in New Mexico (McLemore and McKee, 1988b; McLemore et al., 1999a; McMillan et al., this volume). The similarity in texture with the enclosing rapakivi granite and the high-potassium and low-sodium concentrations are consistent with a metasomatic origin.

Minette

K-rich minette isolated enclaves, swarms of enclaves, and synplutonic dikes in the Jack Creek rapakivi granite range in size from a few centimeters to several meters in diameter. The minette is dark gray, fine–medium grained, and porphyritic with dark mica and, presumably, pyroxene phenocrysts that have been altered into fine-grained amphibole; the main constituents in the groundmass are K-feldspar, dark mica, and amphibole (Kosunen et al., 1999). The enclaves are distinctly finer grained then the enclosing granite. The crenulate to cuspate margins of the synplutonic dikes and many of the enclaves show evidence for intensive commingling with the rapakivi granite host (Fig. 3); quartz and K-feldspar megacrysts have been mechanically incorporated into the minette and the quartz xenocrysts are locally mantled by biotite or hornblende. Adjacent to the minette, feldspars within the rapakivi granite are locally surrounded by biotite and amphibole from the minette. Other minette pillows have sharp to diffuse contacts with the host granite. Locally, coarse-grained pegmatitic phases of the granite form a halo surrounding the minette pillows.

Most minette pillows are rounded and ovoid in shape; cross-sections are typically ellipsoid. Locally angular, lenticular, or cigar-shaped minette pillows are found. Flow foliations are typically absent except locally in the Wild Horse Canyon area where both the rapakivi granite and the enclaves exhibit slight foliation. The foliation continues from the granite into the minette without disruption.

Isolated enclaves scattered throughout the granite pluton are common. The majority of the minette swarms and synplutonic dikes are found along the middle Gila River canyon. The swarms consist of pillows of minette encompassing areas as large as several tens of square meters, locally containing 50–80% minette. Locally, the minette swarms form a linear trend, several tens of meters long and up to 30 m wide; these are termed synplutonic dikes. South of the junction of Foxtail Canyon and the Gila River, a 3-m-long minette dike cuts a large metamorphic xenolith hosted by rapakivi granite. At the contact between the xenolith and rapakivi granite, the dike breaks up into a linear zone of numerous enclaves of minette engulfed by granite. This



FIGURE 3. Photo showing comingling textures along the edges of a minette pillow in Jack Creek rapakivi granite.

zone is 1.5 m wide and continues along strike for at least 5 m. A 0.5-m-wide, pink, fine-grained biotite granite dike cuts both the rapakivi granite and the minette enclaves. The enclave swarms possibly indicate that fountaining (Campbell and Turner, 1986; Lowell and Young, 1999) occurred where the minette magma was injected into the granitic magma and the mafic melt disintegrated into gobules. The areas of concentrated minette enclaves most likely represent source areas where minette magma was injected into the granitic magma.

Pillows of hybrid magma are common on the edges of synplutonic dikes and within swarms of enclaves. The hybrid varieties have incorporated large K-feldspar and quartz phenocrysts that are embayed, corroded, and commonly surrounded by biotite or hornblende. Gradational boundaries are common, although locally the margins are finer grained, indicating a chilled margin.

Redrock granite

The Redrock granite forms the western margin of the Proterozoic terrain north of Redrock, New Mexico. It extends from Smith Canyon southeastward to Ash Creek. This granite consists of four phases: biotite-hornblende granite, hornblende granite, K-feldspar granite and miarolitic biotite granite. These granites are texturally and mineralogically distinct, but they have similar chemical compositions and are interpreted to be a single, zoned pluton. Hedlund (1980a) originally designated this granite and the Jack Creek rapakivi granite as the granite of Redrock. It is proposed in this report to restrict the Redrock granite to the granitic rocks that crop out west and north of Ash Creek, because of chemical differences between the Redrock and Jack Creek rapakivi granites. Small exposures of Redrock granite are found south of Ash Creek.

Biotite-hornblende granite

The medium- to coarse-grained biotite-hornblende granite is orange to red-brown and consists of plagioclase, K-feldspar, quartz, biotite, and hornblende. This granite weathers to dark orange-brown knobby outcrops. Epidote alteration is common. The biotite-hornblende granite grades into the hornblende granite. Xenoliths are rare. The granite is unconformably overlain by Tertiary ash-flow tuff along the western and northern contacts where it is highly weathered and altered.

Hornblende granite

The coarse-grained hornblende granite is orange to red-brown and consists of plagioclase, K-feldspar, quartz, and hornblende; biotite is generally absent. This granite weathers to dark orange-brown knobby outcrops and is slightly foliated (McLemore et al., this volume, p. 48, fig. S.1.5). Xenoliths and pegmatites are rare.

Field relationships suggest that the hornblende granite is possibly younger than the Jack Creek rapakivi granite. At the contact between the hornblende granite and the Jack Creek rapakivi granite east of Ash Creek, the hornblende granite is medium grained and increases in grain size away from the contact (i.e., a chilled margin?). The rapakivi granite is slightly foliated at the sharp intrusive contact with the hornblende ganite (McLemore et al., this volume, p. 49, fig. S.1.7). Pegmatite dikes, probably related to the Redrock granite, intruded the rapakivi granite parallel to the contact between the rapakivi granite and hornblende granite.

K-feldspar granite

Small lenses and dikes of white to light pinkish-gray, fine-grained K-feldspar granite occur within the miarolitic biotite granite. This granite differs from the miarolitic biotite granite by a lighter color, fewer miarolitic cavities, and absence of biotite and xenoliths. However, the K-feldspar granite is intermingled with miarolitic biotite granite. It contains K-feldspar, quartz, and varying amounts of plagioclase. The contacts with the miarolitic biotite granite are gradational. It is most likely a differentiate of the miarolitic biotite granite.

Miarolitic biotite granite

The miarolitic biotite granite is orange–pink and fine–medium grained. It is characterized by miarolitic cavities that are nearly circular to elliptical in shape and range in size from <1–15 cm in diameter. Metamorphic and anorthosite/leucogabbro xenoliths are common in the miarolitic biotite granite.

Along the contact between the miarolitic biotite granite and hornblende granite, small dikes of younger biotite granite and rhyodacite/dacite porphyry dikes intruded the hornblende granite. Locally, the miarolitic biotite granite has brecciated a xenolith or roof pendent of hornblende granite. These field relationships indicate that the miarolitic biotite granite is the younger granite and is interpreted to be the upper part of the pluton. Elsewhere the contact is sharp or covered.

Locally, the miarolitic biotite granite is strongly altered to epidote, quartz, and chlorite along fractures, in thin veins and surrounding miarolitic cavities. Altered zones and thin veins are as much as 2 m wide and are controlled by fractures. The epidote, quartz, and chlorite alteration has formed greenish-gray aggregates or balls within miarolitic cavities up to 20 cm in diameter. Some of these epidote balls occur alone within the granite surrounded by relatively unaltered granite, whereas other areas exhibit vertical trains or linear arrays of these balls connected by fractures containing epidote, quartz, and chlorite. Locally, large (<6 cm long) K-feldspar phenocrysts form a halo surrounding the balls. Hematite is locally abundant in the veins and cavities. This alteration is typical of the degassing of the underlying pluton and resembles in mode of occurrence and appearance greisen or tourmaline alteration of granite elsewhere in the world (Richardson et al., 1990), but with different mineralogy and chemical composition.

Rhyodacite/dacite porphyry dikes

Rhyodacite/dacite porphyry dikes intruded the Redrock granite, especially along the contact between the miarolitic biotite granite and the hornblende granite. They are typically gray-brown to brown and consist of large plagioclase and smaller hornblende and biotite phenocrysts in a fine-grained matrix. Alteration to epidote and chlorite is common.

These dikes previously have been assigned a Cretaceous or Tertiary age because of the similarity in porphyritic texture to Cretaceous–Tertiary andesite porphyry sills and dikes in the northern portion of the area (Hewitt, 1959). However, field relationships indicate that these dikes are Proterozoic. An outcrop on Smith Mountain is brecciated by hornblende granite. Elsewhere fine-grained biotite granite dikes cut the porphyry dikes.

Fine-grained biotite and K-feldspar granite dikes

Orange-pink to gray-pink, fine-grained biotite granite dikes and white to gray, fine-grained K-feldspar dikes intruded the Redrock, Jack Creek rapakivi, and Burro Mountain granites. The intrusive contacts are sharp and locally are chilled along the dike margins. The dikes vary in size up to several meters wide and 100 m long. The dikes have no preferred orientation, with either near vertical or flat-lying (horizontal) dips.

Pegmatites

Pegmatites are relatively rare in the Redrock area as compared to other Proterozoic terrains in New Mexico. They are mostly simple pegmatites, consisting of quartz, plagioclase, K-feldspar, and muscovite with rare biotite. They are pink-red and typically small, from a few centimeters to <1m wide and several tens of meters long. Locally, quartz forms an irregular core that is surrounded by intergrown plagioclase, K-feldspar, and locally, muscovite. Pegmatites occur predominantly in the miarolitic biotite granite but are locally found intruding all of the granitic rocks. Tourmaline and ilmenite occur in a few dikes that intruded the miarolitic biotite granite phase of the Redrock granite.

CHEMISTRY

It is beyond the scope of this report to present the geochemical data,

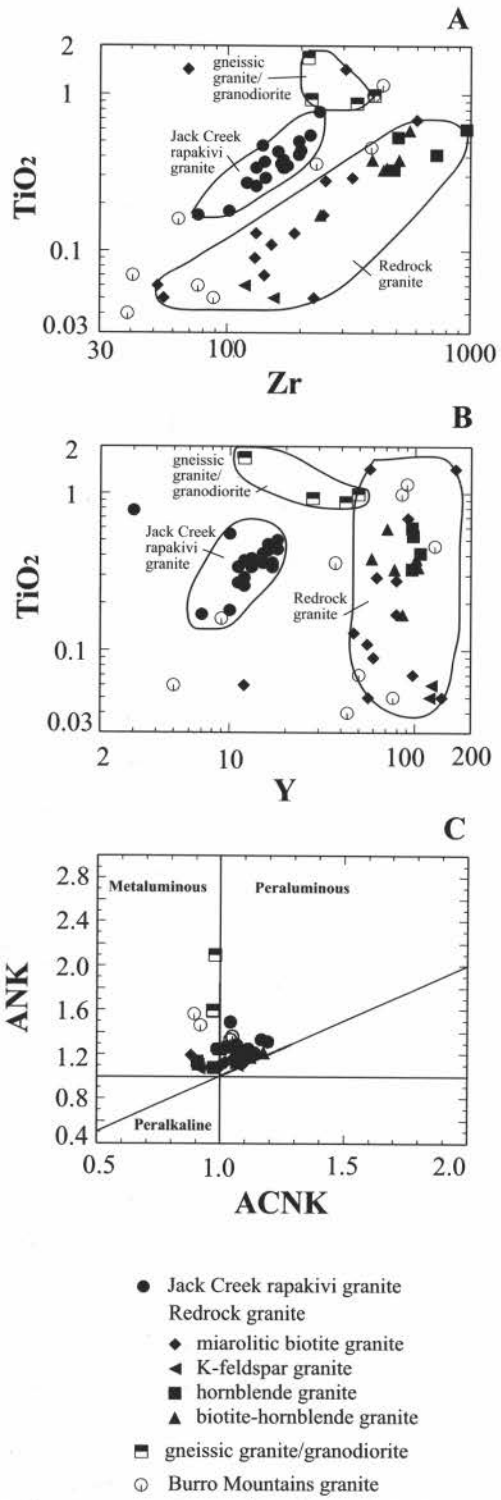


FIGURE 4. Chemical differentiation of the four granitic plutons. ANK-molar $Al_2O_3/(Na_2O+K_2O)$. ACNK- molar $Al_2O_3/(CaO+Na_2O+K_2O)$.

which is only summarized here. At least four separate granitic plutons exist in the Burro Mountains: Burro Mountain granite, gneissic granite/granodiorite, Jack Creek rapakivi granite, and Redrock granite (Fig. 4). All four plutons are calc-alkaline. The Burro Mountain granite is metaluminous to peraluminous (Fig. 4) and contains 25–200 ppm Sr, 10–106 ppm Nb, 5–128 ppm Y, 0.2–3.9% CaO, and 3.1–10% Na_2O+K_2O (unpublished geochemical data). The composition of the Burro Mountain granite is complex and the geochemistry indicates that it consists of more than one pluton. The gneissic granite/granodiorite is

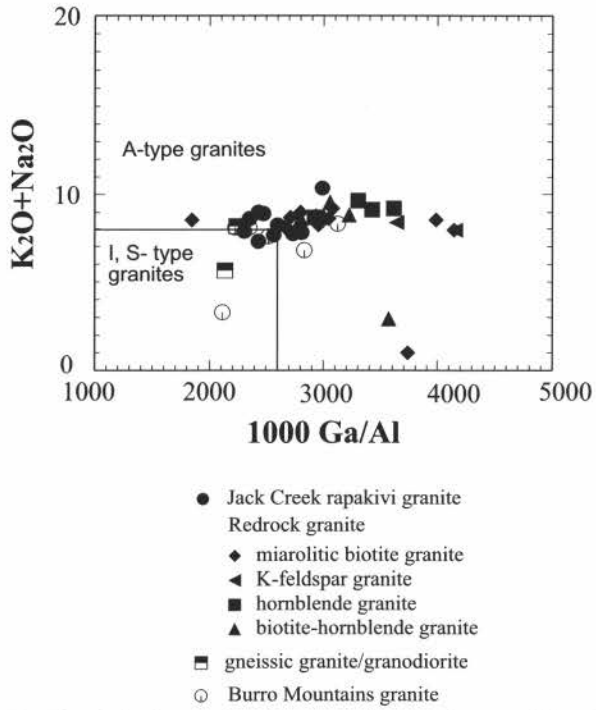


FIGURE 5. Plot of the four granitic plutons on chemical diagrams differentiating A-type granites from S- and I-type granites (Whalen et al., 1987).

metaluminous (Fig. 4) and contains 265–455 ppm Sr, 7–13 ppm Nb, 28–59 ppm Y, 3.9–5.1% CaO, and 5.6–8.1% Na_2O+K_2O. The compositions of the Burro Mountain and gneissic granite/granodiorite granites overlap the compositions of the Redrock granite (Fig. 4). The gneissic granite/granodiorite is lower in SiO_2 and higher in TiO_2, CaO, MnO, Ba, and V than the other three granites.

The Jack Creek and Redrock granites are A-type granites (Fig. 5; Whalen et al., 1987; Eby, 1990). They are typically high in SiO_2 (64–73%), Na_2O+K_2O (7–9%), Zr (130–724 ppm), Ga (13–27 ppm), and low in CaO (0.2–2.4%) and Ba (103–2150 ppm). On Pearce element plots (Fig. 6; Pearce et al., 1984), the Redrock granites plot within the within plate granite (WPG) field and the Jack Creek rapakivi granite plots along the boundaries of syn-collision (Syn-COLG) and volcanic-arc-granite (VAG) fields. The gneissic granite/granodiorite plots along the boundaries of syn-collision (Syn-COLG), volcanic-arc-granite (VAG) and within-plate-granite (WPG) fields. The fact that the granitic rocks do not plot in well defined tectono-chemical fields suggests that their origin is more complex than simple collision of plates, subduction or rifting, or that the fields originally defined for Phanerozoic granites may not necessarily be applicable to Proterozoic granites. The Redrock granite clearly has a different chemical signature than the Jack Creek rapakivi granite and gneissic granite/granodiorite, which is interesting since the Redrock and Jack Creek granites may be similar in age whereas the gneissic granite/granodiorite is older.

The Jack Creek rapakivi granite is a weakly peraluminous, high-K granite, and contains 73–920 ppm Sr, <1–8 ppm Nb, 3–20 ppm Y, low REE, 0.4–2.4% CaO, and 7–9% Na_2O+K_2O. It differs, however, from the classic Proterozoic rapakivi granites of Finland in having, for instance, lower Fe/Mg, Ga/Al, Zr, and HREE. Coeval minettes contain 205–1063 ppm Sr, <1–16 ppm Nb, 1.17–5.37% CaO, 6.2–9.3% Na_2O+K_2O, 934–4100 ppm Ba, 88–388 ppm Ni, and 207–1050 ppm Cr. They are also strongly enriched in the LREE and show a moderate negative Eu anomaly (Eu/Eu* averages 0.60). The Jack Creek rapakivi granite, hybrid, and minette pillows exhibit linear mixing lines (Fig. 7).

The Redrock granite is metaluminous to peraluminous and the most variable in composition of the four plutons (Figs. 4, 6). The four phases of the Redrock granite (biotite-hornblende granite, hornblende granite, K-feldspar granite, and miarolitic biotite granite) are chemically related (Figs. 4, 6). The biotite-hornblende granite contains 31–115

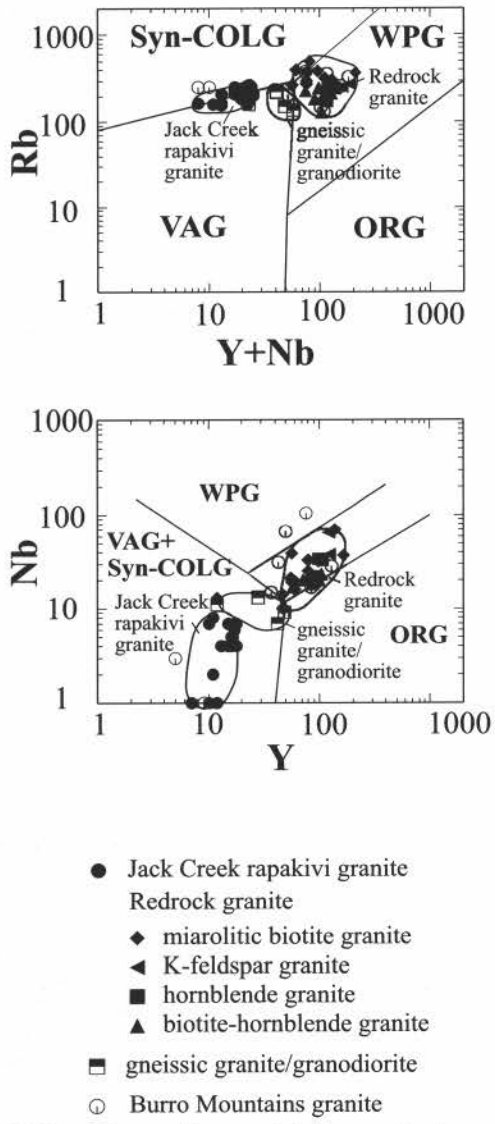


FIGURE 6. Pearce element diagrams of the four granitic plutons (Pearce et al., 1984). Syn-COLG = syn-collision granites. WPG = within-plate granites. VAG = volcanic-arc granites. ORG = orogenic granites.

ppm Sr, 17–23 ppm Nb, 58–104 ppm Y, 0.2–1.3% CaO, and 2.9–9.5% Na_2O+K_2O. The hornblende granite contains 35–95 ppm Sr, 21–33 ppm Nb, 96–106 ppm Y, 0.7–1.8% CaO, and 8–9% Na_2O+K_2O. The K-feldspar granite contains 12–25 ppm Sr, 38–66 ppm Nb, 120–123 ppm Y, 0.2–1.1% CaO, and 8–9% Na_2O+K_2O%. The miarolitic biotite granite contains 11–100 ppm Sr, 10–70 ppm Nb, 12–166 ppm Y, 0.1–2.3% CaO, and 8–9% Na_2O+K_2O%.

The anorthosite/leucogabbro xenoliths are characterized by high CaO (9–12%), MgO (0.3–5%), Al_2O_3 (13–29%), Sr (257–490 ppm) and low SiO_2 (46–51%), K_2O (0.6–2%), and Cr (8–41 ppm). The Redrock anorthosites are similar in chemistry to other anorthosites worldwide (Simmons and Hanson, 1978; Ashwal, 1993).

GEOCHRONOLOGY

For typical metamorphic and plutonic terrains, U/Pb zircon and Sm/Nd isochron age determinations constrain times of intrusion and/or peak metamorphism, whereas $^{40}Ar/^{39}Ar$ results record the thermal history. A combination of these methods has proven very powerful in determining the geologic history of complex regions. The results help define the chronology of events in the study area, but also reveal several ambiguities in the present data set that will be addressed with future dating endeavors.

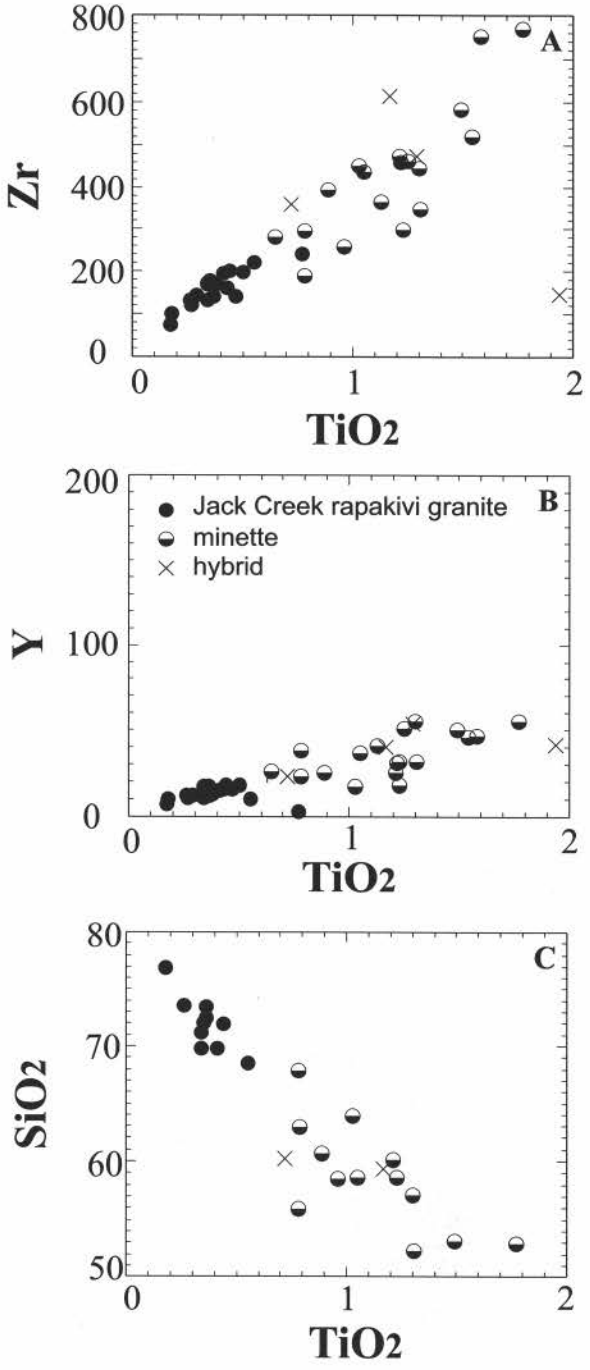


FIGURE 7. Plots showing mixing between the Jack Creek rapakivi granite and minette forming the hybrid pillows.

Stacey and Hedlund (1983) and Hedlund (1980b) reported U/Pb zircon ages for three of the units in the study area (Table 2). Unfortunately, the data are highly discordant and very sparse for each sample, and thus are of limited use for high precision geochronological studies. Zircons from the Bullard Peak metamorphic rocks yielded U/Pb ages of ~1550 Ma which is likely a minimum age for the rock, but may be meaningless with respect to the age of metamorphism. There is little information about the zircons reported by Stacey and Hedlund (1983) and therefore it can not be determined whether the zircons analyzed formed during metamorphism, were inherited, or were a mixed population. For instance, it is just as likely that the peak metamorphism in the area is ca. 1400 Ma and that the zircons analyzed are inherited from the protolith, and have subsequently undergone partial Pb loss. Zircon from the Burro Mountain granite also gave discordant results; however,

TABLE 2. Summary of age determinations. Data available from senior author upon request.

Sample	Published ages (Ma) (Hedlund, 1980a, Stacey and Hedlund, 1983)	$^{40}Ar/^{39}Ar$ (Ma) (mineral dated)	Nd/Sm isochron Ma
Fine-grained biotite dike			
NM84-98		1206 ± 15 (biotite)	
Redrock granite (hornblende granite)			1328 ± 58 (n=4)
NM93-98		1210 ± 5 (hornblende)	
		1204.8 ± 12 (biotite)	
Jack Creek rapakivi granite			1135 ± 71 (n=5)
Red17		1198.0 ± 4.7 (biotite)	
NM17-96		1220.9 ± 3.5 (biotite)	
Minette			1135 ± 71 (n=5)
NM141-98		1420.5 ± 4.5 (biotite)	
NM109-98		1410 ± 5 (hornblende)	
		~1400 (biotite)	
Anorthosite			1326 ± 830 (n=4)
Red7A		1228.5 ± 4.5 (hornblende)	
Red7B		1216.9 ± 5.3 (hornblende)	
Diabase dike	1500–1535 (U-Pb on zircon)		
Gneissic granite/granodiorite	1380 ± 45 (K-Ar)		
Burro Mountain granite	1445 ± 10 (U-Pb on zircon)		
NM134-98		1168.8 ± 11 (biotite)	
Metamorphic rocks	1550–1570 (U-Pb on zircon)		
NM101-98		1202.3 ± 2.4 (muscovite)	

Stacey and Hedlund (1983) suggested an age of 1445 ± "probably no greater than 15 Ma". Evidently, the data are too limited for rigorous error analysis. However, an intrusion age of ca. 1400 Ma is consistent with many well-dated 1400 Ma plutons in the southwestern United States and could be accurate for the Burro Mountain granite. A single zircon analysis from a diabase yielded a common Pb age of ~1500 Ma; but its accuracy is doubtful because the dike intruded the 1400 Ma Burro Mountain granite. The zircon most likely is a xenocryst.

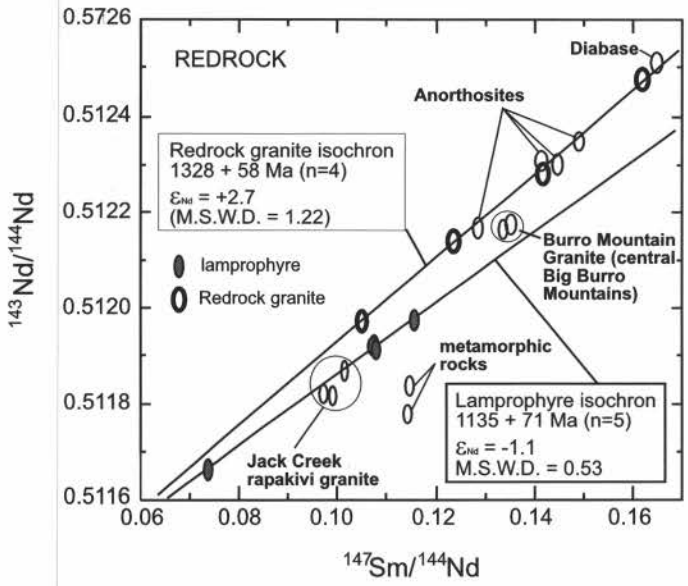


FIGURE 8. Plot of $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ diagram for different rock types in the Redrock area and central Big Burro Mountains. Two isochrons are shown, one for the Redrock granite (four data points with thick black margins) and one for the minettes associated with the Jack Creek rapakivi granite (five shaded data points). The size of the symbols is proportional to the 2-σ errors on $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ (unpublished data by the authors). M.S.W.D. denotes Mean Square of Weighted Deviates (unpublished data by the authors).

Nd isotopic results are particularly useful as tracers of mantle and crustal evolution, and can be used for isochron construction provided there is enough variation in Sm/Nd values of isochronous samples. Sm/Nd isochron analysis of the Redrock granite (hornblende, biotite-hornblende, and miarolitic biotite granite) defines an age of 1328 ± 58 Ma (2σ) and initial ε_{Ndi} of +2.7 with an MSWD (Mean Square of Weighted Deviates goodness of fit indicator) of 1.22 (Fig. 8, Table 2). The low MSWD suggests that the calculated age represents the crystallization age of the granites and that the phases of the Redrock granite constitute a zoned pluton of single age. Five minette samples fall on a well-defined (MSWD = 0.53) isochron with an age of 1135 ± 71 Ma and initial ε_{Ndi} of –1.1 (Table 2, Fig. 8). The Jack Creek rapakivi granite shows too narrow a spread in Sm/Nd ratio to define an isochron; however, three analyzed samples fall on the trend defined by the minettes and the rapakivi granite is coeval with the minette on the basis of field relations. The Sm/Nd data of the anorthosites give a poor isochron age of 1326 ± 830 Ma and do not provide chronologically meaningful information for the age of the anorthosite (Table 2). The anorthosite and diabase fall on the Redrock granite Sm/Nd isochron and may indicate that they are similar in age.

Several micas and amphiboles from the major rock units in the study area were dated by the $^{40}Ar/^{39}Ar$-age-spectrum method (Fig. 9, Table 2). All of the mineral ages cluster at ca. 1200 Ma except for results from the minettes, which give older apparent ages. Sample NM-109 minette yields highly disturbed hornblende and biotite age spectra; however, most apparent ages are older than 1200 Ma (Fig. 9). Sample NM-141, also from a minette, has a fairly flat age spectrum with ~85% of the argon released giving a weighted mean age of 1421 ± 5 Ma (Fig. 9, Table 2). These results are inconsistent with the 1131 ± 71 Ma Sm/Nd isochron age of the minettes and are discussed below. The minerals which yield ca. 1200 Ma argon ages generally yield well-behaved age spectra that are characterized by significant flat segments with typical 2σ uncertainties of ~5 to 15 Ma (Fig. 9; Table 2).

The closure temperature of K-bearing minerals is variable with nominal values of ~500°C for hornblende; 375°C for muscovite, and 300°C for biotite (McDougall and Harrison, 1999). The concordance of the hornblende, biotite, and muscovite ages at ~1200 Ma indicates that the samples were cooling rapidly at this time. Argon mineral ages of 1200

Ma are uncommon for New Mexico and the southwestern United States in general (e.g., Karlstrom et al., 1997). Also, this age does not appear to coincide with either the ~1300 Ma Redrock granite or the ~1130 Ma minette Sm/Nd isochron ages. One explanation for the 1200 Ma argon results would be a relatively rapid uplift (denudational) event at this time, which brought the rocks from above 500°C to below 300°C. This would require substantial (5–10 km) denudation, and such an "event" has not been recognized regionally. Another explanation would be resetting of the argon clocks during a 1200 Ma heating event. At first glance this does not appear applicable because the Redrock granite intrusion is ~1300 Ma and the minettes are ~1130 Ma. Partial argon loss during 1130 Ma minette/rapakivi intrusion can not explain the results, because of the concordance of hornblende/biotite ages. Partially resetting a hornblende to 1200 Ma during an 1130 Ma event would cause complete argon loss from biotite, thereby yielding highly discordant hornblende/biotite ages. A high-temperature resetting event at 1200 Ma is attractive, as it would be short-lived and explain the near concordance of hornblende/mica ages. Perhaps the large uncertainties of the Sm/Nd isochron ages would allow the minette/rapakivi to be nearer 1200 Ma and thus become the geological expression of the event that reset the argon ages. Clearly, more precise intrusion ages for the Redrock granite and minette/rapakivi granite will be pivotal towards understanding the geochronology in the Burro Mountain area.

Lastly, the discordance between the argon ages, Sm/Nd isochron ages, and field relationships needs to be addressed. The Sm/Nd isochron ages may not be crystallization ages, but they may reflect later thermal events, mixing of mafic and granitic magma with crustal material, assimilation-fractional crystallization of crustal material, or they could be meaningless. The highly complex results from NM109-98 can not be used to strongly argue against the 1131 Ma Sm/Nd isochron age. However NM141-98 biotite appears straightforward and its ~1420 Ma age is a common age for many Proterozoic rocks from the southwestern USA. At this point we can not present a satisfactory explanation for the discrepancy of the argon and Sm/Nd results from the minette.

Nd ISOTOPES

Preliminary interpretation of Nd isotopic data (unpublished) suggests that the granites in the Redrock area can be divided into three different plutons of different age and composition that are distinct in terms of their protolith history (Fig. 8). If the Jack Creek rapakivi granite is ≤1200 Ma old, it was derived from a source characterized by subtle long-term LREE depletion. The Redrock granite shows a clearly more radiogeneic initial Nd isotopic composition and was probably derived from a slightly depleted protolith (Fig. 8). Both granites are clearly more juvenile (Nd model ages ~1600 Ma) than the metamorphic country rocks (these show Nd model ages of ~1900 Ma) and their protoliths may thus have included a significant Middle Proterozoic mafic lower crust/subcontinental lithospheric mantle component. The nature of the latter is yet to be determined in detail. The Burro Mountain granite ((Nd [calculated at 1330 Ma for comparison] value ~ +1.5) probably had a slightly less radiogeneic protolith than the Redrock granite or the Jack Creek rapakivi granite (Fig. 8).

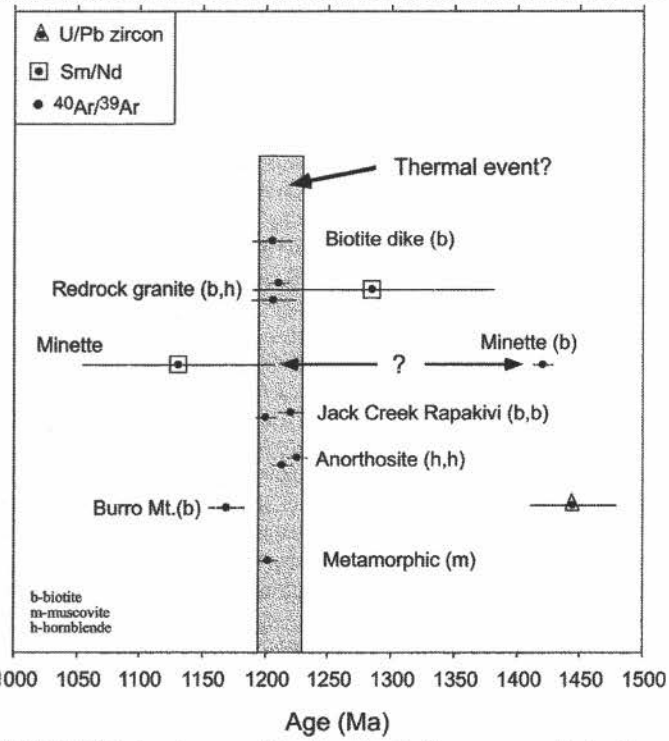


FIGURE 9. Plot showing age relationships. b = biotite, m = muscovite, h = hornblende.

PRELIMINARY CONCLUSIONS

The age of the granites and minettes remains unclear and will hopefully be resolved by additional U/Pb dating of zircons. The available data indicate that the Redrock granite is ≥1200 Ma and the Jack Creek rapakivi granite and minette are ≥1100 Ma. The number of $^{40}Ar/^{39}Ar$ age dates clustering about 1200 Ma (Fig. 9) strongly suggests that a heating event or uplift occurred at that time.

Interpretation of geochemical and isotopic data indicates that the Redrock granite, anorthosites, Jack Creek rapakivi granite, Burro Mountain granite, and metamorphic rocks were derived from distinctly different protoliths. The anorthosites and diabase probably tapped a moderately depleted mantle source. The Jack Creek rapakivi granite was presumably derived from a source characterized by subtle, long-term LREE enrichment, whereas that of the Redrock granite pluton was slightly depleted. Both were clearly more juvenile (Nd model ages ~1600 Ma) in nature than the metamorphic rocks of the region (Nd model ages ~1900 Ma) and may include a significant Middle Proterozoic mafic lower crust/subbcontinental lithospheric mantle component. The metamorphic rocks of the region register an older signature than what has been considered typical of the Nd province 3 of the western United States (Bennett and DePaolo, 1987).

Continued mapping of the granitic rocks in the northern Burro Mountains is underway. Additional petrographic, geochemical, and isotopic analyses are planned to better characterize and date these rocks, and to define their petrogenesis and tectonic setting.

ACKNOWLEDGMENTS

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