Proterozoic Rocks and Their Mineralization

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Early Proterozoic Rocks

Early Proterozoic rocks constitute one-third or more of the area of bedrock exposure in the East Mojave National Scenic Area (EMNSA) (pl. 1; see also fig. 4). These rocks received very little attention until the past few years. Earliest studies were part of regional mapping investigations by Hewett (1956), who distinguished two Proterozoic rock units: (1) gneiss and granite, and (2) syenite and shonkinite. The former unit is now known to be Early Proterozoic in age. The latter unit encompasses Middle Proterozoic intrusions at Mountain Pass. Reconnaissance geochronologic studies (Wasserburg and others, 1959; Silver and others, 1961; Lanphere, 1964) established that the crystalline Proterozoic rocks in the Death Valley (25 km northwest of the EMNSA) and eastern Mojave Desert regions are approximately 1.7 to 1.6 billion years old (Ga). Mapping studies of the area through the 1970s (Providence Mountains, Hazzard (1954); Mountain Pass area, Olson and others (1954); Clark Mountain Range, Clary (1967); Clark Mountain Range and Ivanpah Mountains, Burchfiel and Davis (1971); McCullough Range, Bingler and Bonham (1972); Old Dad Mountain, Dunne (1977)) generally showed one or only a few map units designated as Early Proterozoic in age and gave sketchy lithologic and petrographic descriptions for them. As a consequence, reviews of the eastern Mojave Desert region (Miller (1946); McCulloh (1954); Burchfiel and Davis (1981)) emphasized the paucity of data on the Early Proterozoic rocks and the need for additional research.

Geologic mapping and geochronologic, isotopic, and petrologic studies during the 1980s have led to major advances in understanding the Early Proterozoic crustal evolution of the region. Geologic mapping in and near the EMNSA (hills near Halloran Spring, DeWitt and others (1984); New York Mountains, Miller and others (1986) and Miller and Wooden (1993); Providence Mountains, Goldfarb and others (1988); McCullough Range (10 km north in southern Nevada), Anderson and others (1985)) locally has resulted in extensive subdivision of the Early Proterozoic rocks. Wooden and Miller (1990) and Miller and Wooden (1993) summarized the Proterozoic evolution of this part of the Mojave Desert and presented most of the new data that form the basis for this review.

The Early Proterozoic history of the northeastern part of the Mojave Desert is primarily one of plutonism and metamorphism. DeWitt and others (1984) dated gneissic granites in the hills near Halloran Spring as about 1.71 Ga, setting the stage for the ensuing documentation of a 1.705–Ga granulite-facies metamorphic event (the Ivanpah orogeny), as well as pre-, syn-, and post-metamorphic granitoids (Wooden and Miller, 1990). Metaplutonic and plutonic rocks that range in age from 1.76 to 1.66 Ga are now documented, and some of their wallrocks contain zircons that are 700 m.y. older than the oldest granitoids. The emerging picture is one of a 1.8–Ga sedimentary and volcanic province that, in part, received detritus from much older sources (1.9, 2.3, and 2.5 Ga) and was probably built upon a 2.5–Ga basement. These older rocks were intruded, and perhaps deformed and metamorphosed, at 1.76 and 1.73 Ga; the magmas were mafic and metaluminous in some cases and potassium rich in others. Between 1.71 and 1.695 Ga, a major orogenic event, the Ivanpah orogeny, thoroughly migmatized older rocks, as well as synkinematic potassium-rich granitoids. The hallmark of the event is widespread migmatite, which in many places is characterized by abundant leucocratic-granitoid layers and by ubiquitous garnet. Metamorphism was at low-pressure granulite facies (Thomas and others, 1988; Young, 1989; Young and others, 1989) in this region. Following the Ivanpah orogeny, granitoids were emplaced in a north-south-trending zone in the New York Mountains and McCullough Range as two intrusive suites, the first at about 1.695 to 1.675 Ga and the second at about 1.8 to 1.66 Ga. Although these two suites of granitoids apparently overlap in age, the suites can be separated by differences in chemistry and style of intrusion; the younger of the two is calc-alkaline and compositionally expanded. Groups of plutons emplaced during these plutonic events are of batholithic dimensions and display an evolution from peraluminous potassium-rich magmas to metaluminous calc-alkaline magmas. Events that followed the youngest Early Proterozoic magmatism at about 1.66 Ga are sketchy, but they include the following: (1) formation of mylonite belts, perhaps during prolonged cooling through the Early and Middle Proterozoic; (2) anorogenic magmatism at about 1.4 Ga, including emplacement of carbonatite at Mountain Pass, to be described below; and (3) diabase-sheet intrusion at about 1.1 Ga.

Protoliths for the supracrustal gneisses are variable and include a variety of sedimentary and volcanic rock types (Hewett, 1956; DeWitt and others, 1984, 1989; Anderson and others, 1985; Miller and others, 1986; Wooden and Miller, 1990). Inferred sedimentary rock types are fine-grained aluminous and quartz-rich rocks such as shale and siltstone, immature sandstone, volcaniclastic sandstone, and quartzite, the latter of which is restricted mostly to the hills near Halloran Spring. Volcanic protoliths are most commonly of felsic compositions, such as dacite and rhyodacite. In some places, distinguishing between intrusive and extrusive origins is difficult because the rocks have undergone granulite-facies metamorphism. For example, in the Providence Mountains and Mid Hills, a bimodal suite of felsic and mafic gneisses may represent either volcanic or intrusive rocks (Wooden and Miller, 1990). Contact relations and textures best support an intrusive origin (Miller and Wooden, 1993). Minimum ages for the supracrustal rocks range from 1.7 to about 2.0 Ga, on the basis of $^{207}Pb/^{206}Pb$ ages determined by conventional U–Pb zircon geochronology (Wooden and Miller, 1990). Spot ion-probe analyses of single zircon grains yield clusters of ages at about 2.5 Ga, 2.3 Ga, 1.9 Ga, and 1.8 Ga (Miller and Wooden, 1994). The simplest interpretation of these ages is that they represent ages of igneous zircons from several source terranes; and so, the older zircons were redeposited with the youngest group of syndepositional volcanic and sedimentary rock strata at about 1.8 Ga. A minimum age for these rocks is 1.76 Ga, the age of the oldest dated plutonic suite that intrudes the supracrustal gneiss.

The EMNSA and nearby areas in southeastern California, southern Nevada, and northwestern Arizona are underlain by Early Proterozoic crust (Mojave crustal province of Wooden and Miller, 1990) that is isotopically and chronologically anomalous compared to other Early Proterozoic crust throughout the rest of the western United States. Neodymium-model ages for crust formation are 2.3 to 2.0 Ga in the Mojave crustal province, which suggests that this terrane formed from the mantle at 2.3 to 2.0 Ga or that the terrane formed at approximately 1.9 to 1.65 Ga and incorporated a significant component of Archean crust (Bennett and DePaolo, 1984, 1987). Because of the general lack of crust in the 2.3– to 2.0–Ga age range in the United States, Bennett and DePaolo (1987) preferred the latter interpretation and, furthermore, suggested that this terrane was transported on a left-lateral fault at least 400 km from the north where it both formed against and incorporated Archean crust. Lead-isotope characteristics (Wooden and others, 1988; Wooden and Miller, 1990) require that the Mojave crustal province incorporated lead from an Archean reservoir; lead in1.7-Ga–rocks is more radiogenic than would be expected if it were derived directly from the mantle. The Nd–model ages coupled with U–Pb detrital-zircon data suggest 2.2 to 1.8 Ga as the likely age for an event in which Archean clastic materials, possibly from the Wyoming Province, were deposited along with synorogenic deposits. Similar deposits may have been subducted, which allowed the addition of radiogenic lead into the mantle from which the Mojave crustal province was derived (Wooden and Miller, 1990).

Middle Proterozoic Granite

Several areas adjacent to the north-central part of the EMNSA are underlain by distinctive intrusive rocks whose age is approximately 1.4 Ga. The rocks principally consist of syenite, shonkinite, carbonatite, and granite; they crop out in the vicinity of Mountain Pass just outside the EMNSA (pl. 1). Although the mafic and alkalic rocks of this group are unusual, the granites are similar to others of this age that are widespread in southern California, in central and southern Arizona, and in southern Nevada (Anderson and Bender, 1989; Anderson, 1989). These rocks are commonly called “anorogenic,” as their emplacement is generally not associated with regional or, commonly, even local deformation. They are generally coarse grained and characterized by large, conspicuous phenocrysts of K–feldspar. Most plutons are granite, although some are granodiorite, quartz monzodiorite, and quartz monzonite. Common accessory and minor minerals include biotite, hornblende or muscovite, fluorapatite, zircon, and magnetite. Highly evolved members of the 1.4–Ga granitoid suite are enriched in Rb, Th, and U, and depleted in Ba and Sr.

Middle Proterozoic igneous rocks of the Mountain Pass area are described more fully in the section below entitled “Ultrapotassic Rocks, Carbonatite, and Rare Earth Element Deposit, Mountain Pass, Southern California.” Middle(?) Proterozoic porphyritic granite in the eastern Vontrigger Hills is grouped with other granitoids on the geologic map (pl. 1). These rocks are coarse-grained biotite granite that contains megacrysts of K–feldspar and are undated.

Middle Proterozoic Diabase

Middle Proterozoic diabase dikes are known in the northeastern part of the EMNSA (Miller and Wooden, 1994) and are likely present as sparse small dikes in other parts of the study area. The dikes are generally less than 2 m thick; typically altered, mostly deuterically; and a few tens of meters in length, too small to show at the scale of the geologic map (pl. 1). They are part of a diabase suite emplaced at about1.1 Ga throughout the southwestern United States (Hammond, 1990; Howard, 1991; Conway and others, 1993; Conway, 1994). Widespread large dikes and sills are present in the southern Death Valley and Kingston Range region, about 25 km north-northwest of the EMNSA (Wright, 1968; Wright and others, 1976). Dikes and sheets are present in mountain ranges of the Mojave Desert south of the EMNSA (Howard, 1991) and are widespread in northwestern Arizona (Albin and Karlstrom, 1991; Bryant, 1992a, b; Conway, 1993; Conway and others, 1993; Conway, unpub. data, 1995). Diabase has been dated at numerous places in the Southwest at between 1.07 and 1.10 Ga, in the Death Valley area at 1,087±3 and 1,069±3 Ma (Heaman and Grotzinger, 1992), and in northwestern Arizona at 1.08 Ga (Shastri and others, 1991).

Examination of diabase dikes at numerous localities throughout the Southwest, including most of the radiometrically dated localities, indicates that 1.1–Ga diabase has a distinctive ophitic texture that in most cases clearly distinguishes it from mafic dikes of any other age. There is little doubt that the diabase dikes in the EMNSA are of the regional Middle Proterozoic diabase suite, although no systematic work has yet been done on the diabase dikes in the EMNSA.

Proterozoic Mineralization

Hewett (1956) noted that, although many mineral occurrences are hosted by Early Proterozoic gneiss in the eastern Mojave Desert region, the major periods of ore deposition were the Mesozoic and the late Tertiary. He furthermore concluded that no clear evidence exists for widespread Early Proterozoic mineralization in the area. However, limited evidence does exist for some minor mineralization of Proterozoic age, in addition to the rare earth element deposits associated with the 1,400–Ma carbonatite at Mountain Pass (see section below entitled "Ultrapotassic Rocks, Carbonatite, and Rare Earth Element Deposit, Mountain Pass, Southern California").

Minor amounts of rare earth elements and thorium have been mined from pegmatite in the New York Mountains (Miller and others, 1986). Similar pegmatites are common within the Early Proterozoic gneiss terrane throughout the EMNSA and have been interpreted to be the source of most of the anomalous concentrations of these elements in stream-sediment geochemical data (see section below entitled "Geochemistry"; see also Miller and others, 1986). Volborth (1962) suggested that these allanite-bearing pegmatites are related genetically to Mountain Pass-type syenite-carbonatite, but the field evidence of Miller and others (1986) indicated that the pegmatites are older, presumably Early Proterozoic, and therefore unrelated to a Middle Proterozoic carbonatite system.

Some suggestion of minor amounts of Proterozoic mineralization exists in the Ivanpah Mountains. At Mineral Spring, in the northern Ivanpah Mountains southeast of Mineral Hill, intensely fractured Early Proterozoic migmatite and granitoid gneiss (unit Xg_1, pl. 1) is cut by numerous quartz-galena-chalcopyrite veins. Most quartz is milky white and generally shows variable amounts of staining by secondary copper minerals. Most of the mineralized rock seems to be concentrated along a 1– to 2–m-wide fault zone that contains abundant gossan along its trace, which strikes N. 10° E. and dips 25° W. These veins are foliated and concordant with the fabric of the surrounding gneisses. Some veins have highly deformed, schistose selvages of brown carbonate-rich material along their margins; in places, some formerly clay rich zones are now recrystallized to white mica. The presence of jasperoidal-appearing material along the structure and its subsequent brecciation and neomineralization suggest that multiple episodes of mineralization have occurred in the general area. Mesozoic breccia development and sericitization are common in Nevada adjacent to the EMNSA (Miller and Wooden, 1994). We tentatively assign the deformed quartz-galena-chalcopyrite veins to a

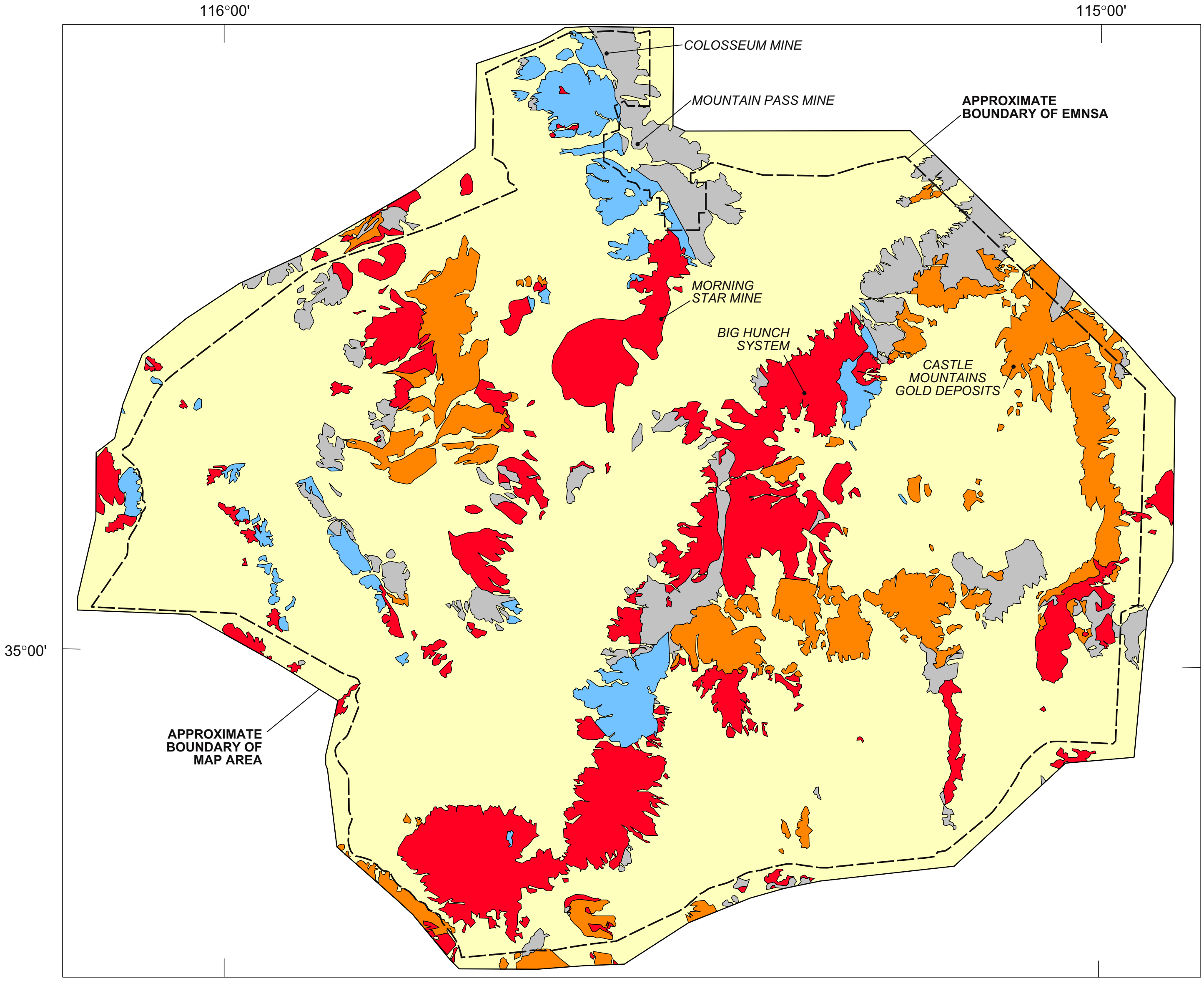
Middle Proterozoic mineralization event related to magmatic rocks of this age in the immediately surrounding area (see section below entitled “Geochemistry”). However, some or all veins in the general area of Mineral Spring also could be Mesozoic in age.

Some mineral occurrences are associated with diabase dikes and sills examined in the northernmost New York Mountains. Several closely spaced, 2– to 4–m-wide diabase dikes strike N. 60° to 70° W. and dip 60° to 70° NE. approximately 1 to 2 km east of the Albermarle Mine (Miller and others, 1986; U.S. Bureau of Mines, 1990a, map no. 216). They intrude brecciated gray to white massive quartz and underlying mylonitized leucocratic granitoid gneiss; foliation in the granitoid gneiss and predominant shear surfaces in the breccia dip about 25° to 30° SW. Two shafts and numerous excavations are present in this area, many of which explore gossaniferous polymetallic quartz-sulfide veins as much as 1 m wide that are present as selvages to diabase sills. The diabase dikes and sills and their associated veins are undeformed; both clearly postdate deformation of the vein quartz and granitoid gneiss. The diabase also is locally altered in the vicinity of the veins. Systematic juxtaposition of dikes and quartz-sulfide veins suggests a genetic relation.

Similar diabase dikes and quartz-vein deposits were described elsewhere in the Southwest (Hewitt, 1959; Beard, 1987; Silberman and Wenrich, 1993; Wenrich and Silberman, 1993). Vein-type mineralization related to the emplacement of 1.1–Ga diabase dikes in Early Proterozoic crystalline rocks in the EMNSA may be more widespread than recognized previously.

Diabase dikes intruding the southern Death Valley area formed talc deposits by contact metamorphism of a carbonate member of the Middle Proterozoic Crystal Spring Formation of the Middle and Late Proterozoic Pahrump Group (Wright, 1968). The region between the southern Panamint Range, 35 km northwest of the EMNSA, and the Kingston Range contains 29 deposits that produced 1.09 million tonnes of talc ore. Talc and clay mines are present within a few kilometers of the north boundary of the EMNSA in the hills near Halloran Spring; whether these mines are associated with diabase is unknown. Additionally, asbestos, iron, and uranium deposits in the Middle Proterozoic Apache Group in central Arizona were formed by processes related to emplacement of large diabase sills (Wrucke and others, 1986).

The locations of many mineral deposits in both the Death Valley and central Arizona regions are controlled by the nature of the intruded sedimentary rocks. Host rocks suitable to the formation of such ore deposits, notably the Pahrump Group, are virtually absent in the EMNSA. Absence of host rocks and the scarcity of diabase sills suggests that little, if any, potential exists for talc, asbestos, iron, and uranium deposits associated with diabase in the study area.



EXPLANATION

- Quaternary and Tertiary sedimentary rocks
- Quaternary and Tertiary volcanic rocks
- Mesozoic plutonic rocks
- Mesozoic to Late Proterozoic sedimentary and volcanic rocks
- Proterozoic plutonic and metamorphic rocks
- Contact—Faults omitted for simplicity
- Approximate boundary of East Mojave National Scenic Area

Figure 4. Generalized geologic map of East Mojave National Scenic Area (EMNSA), Calif., showing locations of major mineral occurrences. Simplified from Plate 1.