MESOZOIC ROCKS

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Triassic Plutons

Triassic plutonic rocks are widely scattered in regions mostly west and southwest of the EMNSA (Barth and others, 1991; Miller, 1978). In the Clark Mountain area, several small dioritic stocks intrude Paleozoic strata, and one of these bodies has yielded K-Ar hornblende ages of 190 and 200 Ma (Burchfiel and Davis, 1971; Mueller and others, 1979). However, preliminary U-Pb zircon ages for these bodies are Late Jurassic (J.D. Walker, 1993, oral commun.). Evidently, the hornblende contained excess argon, resulting in ages spuriously old. No Triassic U-Pb ages have been reported for plutons in the EMNSA, but few candidates have been dated by U-Pb. A dioritic orthogneiss unit in the Granite Mountains, assigned a probable Triassic age by Howard and others (1987), is now known to be Jurassic (Young and others, 1992). Small bodies of hornblende monzonite, commonly present between the Teutonia batholith and septa of Paleozoic marble in the western New York Mounains, is similar to Triassic monzonites known in the western Mojave Desert. This hornblende monzonite is younger than Paleozoic rocks and older than the Early Cretaceous Mid Hills Adamellite.

Triassic Sedimentary Rocks

In most of the ranges of the EMNSA that contain latest Proterozoic and Paleozoic sequences (see previous section), these strata are conformably overlain by reddish sandstone, limestone, and shaley limestone, or their metamorphosed equivalents. These rocks are correlated with the Early to Middle Triassic Moenkopi Formation (Burchfiel and Davis, 1971, 1977; Walker, 1987). In the Providence Mountains, this unit is approximately 300 m thick and contains Early Triassic fossils. In many ranges, these rocks are metamorphosed to distinctive calc-silicate rock (Stone and others, 1983).

In the Mescal Range, a unit of sandstone, shale, and limestone stratigraphically above the Moenkopi Formation and below a Jurassic sandstone unit was correlated with the Late Triassic Chinle Formation by Hewett (1956). This correlation was questioned by Marzolf (1983), who considered several Jurassic units to lie directly on the Moenkopi. Possible Chinle-correlative rocks have not been reported elsewhere in the EMNSA.

Mesozoic Volcanic and Hypabyssal Rocks

Several ranges within the EMNSA contain volcanic and volcaniclastic rocks, intercalated sedimentary rocks, and related hypabyssal rocks of Triassic and (or) Jurassic age.

Stratigraphic sequences, in varying degrees of preservation, are exposed in four areas: the Mescal Range, the Old Dad Mountain-Cow Hole Mountains-Soda Mountains area, the New York Mountains, and the Providence Mountains. In a few other areas, metamorphosed or hydrothermally altered Triassic and (or) Jurassic volcanic, hypabyssal, and sedimentary rocks are present as small pendants in Jurassic or Cretaceous plutons, or as slivers in fault zones. Among these small relicts, Jurassic rocks are probably more common than Triassic rocks. Owing to common metamorphism or alteration, and to lack of study, little is known about the petrology and geochemistry of Triassic and Jurassic volcanic rocks in the EMNSA.

A sequence of diverse volcanic and sedimentary rocks, more than 3 km thick, in Old Dad Mountain and the Cow Hole Mountains consists of interbedded intermediate to silicic lava flows and flow breccias, quartz arenite, sandstone and siltstone, sedimentary breccia and megabreccia, silicic ignimbrite, and other minor rock types (Busby-Spera, 1988; Busby-Spera and others, 1989; Marzolf, 1983; 1988; 1991). U-Pb zircon ages of some of the volcanic rocks indicate that this sequence is approximately 170 Ma, which is Middle Jurassic according to the geologic time scale of Harland and others (1989). A generally similar sequence of rocks is present in the Soda Mountains, near the west edge of the EMNSA (Grose, 1959).

The quartz arenite units in the Mescal Range, Old Dad Mountain, and the Cowhole Mountains are in part eolian. Until recently, these quartz arenites were generally correlated with the Early Jurassic (Peterson and Pipiringos, 1979) eolian Aztec Sandstone of the southern Great Basin and Navajo Sandstone of the Colorado Plateau. However, the U-Pb ages cited above indicate that the Jurassic quartz arenites in these ranges, and probably others in the EMNSA, may correlate with the Carmel Formation or the Entrada Sandstone of the Colorado Plateau. Poor age constraints for the Colorado Plateau units permit either correlation.

In the Providence Mountains, intermediate to silicic volcanic, volcaniclastic, and hypabyssal rocks, in part intensely altered, have been mapped by Miller and others (1985) and Goldfarb and others (1988). The hypabyssal rocks typically have granitic textures. These igneous rocks in part overlie the Moenkopi Formation, and are probably Triassic and (or) Jurassic in age (Walker, 1987). In some places, the volcanic rocks contain intercalated conglomerate and siltstone.

In the New York Mountains, a sequence of metamorphosed volcanic rocks approximately 250 m thick overlies the Moenkopi Formation, and is in turn overlain by a metasedimentary unit approximately 70 m thick (Burchfiel and Davis, 1977). The volcanic rocks are silicic in composition, include breccia or agglomerate, and contain subordinate intercalated metasiltstone and, near the base of the unit, metaconglomerate. The metasedimentary unit comprises siltstone, conglomerate, and tuffaceous sandstone and siltstone. The conglomerate beds contain clasts derived from the underlying volcanic unit. These two units could be either Triassic or Jurassic in age; the latter is perhaps more likely. The metavolcanic rocks are generally schistose or mylonitic; this fabric probably is largely inherited from original welded tuff textures. Metasedimentary lithologies range from argillite to schist. Both the volcanic and sedimentary units in the New York Mountains contain metamorphic biotite.

In the Mescal Range, a unit of crossbedded arenitic sandstone approximately 250 m thick contains dinosaur tracks, the only dinosaur tracks known in California (Reynolds, 1983). It is overlain by a sequence, approximately 200 m thick, of basaltic, dacitic, and rhyolitic flow breccias and lava flows (Hewett, 1956; Fleck and others, in press). These volcanic rocks have not been studied in detail, but are dated by K-Ar and Rb-Sr as Early Cretaceous, about 117 Ma (Fleck and others, in press), and therefore differ in age as well as composition from Jurassic volcanic sequences in other parts of the EMNSA.

Jurassic and Cretaceous Plutonic Rocks

Introduction

Plutons known to be of Jurassic age or of Cretaceous age, based upon U-Pb geochronology, are common in the EMNSA (pl.1; fig. 4). Other plutons are definitely or almost certainly Mesozoic, but it is uncertain whether they are Jurassic or Cretaceous. The Jurassic and Cretaceous plutons and ranges in which they crop out within the EMNSA are too numerous to list or describe individually. Rather, the descriptions below focus upon typical or relatively well-studied plutons, and upon features of special interest.

Both the Jurassic and the Cretaceous plutons within the EMNSA are small parts of magmatic belts that extended through much of the southern Cordillera and are oblique to one another (Miller and Barton, 1990; Fox and Miller, 1990; Tosdal and others, 1990). The northeast margin of the composite magmatic belt lies wthin the EMNSA in the central parts of the Ivanpah and New York Mountains.

Known Jurassic plutons and Cretaceous plutons in the EMNSA region generally differ in petrology and geochemistry. Miller and others (1982), Miller and others (1985), Howard and others (1987), and Fox and Miller (1990) have summarized the characteristics of Jurassic and Cretaceous plutonic rocks in the Granite Mountains, southern Providence Mountains, and Colton Hills of the southern EMNSA. The Cretaceous granitoids are characterized by relatively low color index, white to buff or flesh-colored feldspars, and absence of clots of mafic minerals. In contrast, the Jurassic granitoids commonly are more heterogeneous, contain less quartz, more commonly are conspicuously sphene-bearing, are more potassic, have higher color index, contain lavender, grey, or pinkish alkali feldspar, and contain clots of mafic minerals. In some places, Jurassic plutons are associated with magnetite skarn deposits or zones of extensive albitization, neither of which is documented for Cretaceous plutons. For some Mesozoic plutons for which U-Pb ages have not been determined, a reasonable inference as to a Jurassic or a Cretaceous age can thus be made from the overall petrology or composition of the plutons. Such estimates are probably most applicable to granodiorite and granite compositions, and have a lower probability of being correct for dioritic or gabbroic rocks. In the report, we follow the IUGS classification scheme (Streckeisen and others, 1973) adopted for plutonic igneous rocks.

Geochronological data, much of it unpublished, for plutons in the EMNSA hint at multiple intrusive episodes for each of the Jurassic and Cretaceous groups of plutons. Many Jurassic plutons appear to be 160 to 165 Ma, but some plutons and dikes are as young as 150 to 145 Ma. Cretaceous plutons appear to belong to a late Early to early Late Cretaceous intrusive event, 90-100 Ma, and a late Late Cretaceous event, 70-75 Ma. General distingushing characteristics of Jurassic and Cretaceous plutons are maintained despite episodicity within the two groups.

Jurassic Plutonic Rocks

Widespread emplacement of Jurassic plutons followed by approximately 50 m.y. the emplacement of scattered Triassic plutons in the Mojave Desert region (Tosdal and others, 1990; Anderson and others, 1991). The most thoroughly studied Jurassic plutonic rocks in the region of the EMNSA are those in the area of the southern Bristol Mountains, southern Providence Mountains, and Colton Hills (Miller and others, 1985; Fox and Miller, 1990); Granite Mountains (Young and others, 1992); and Clipper Mountains (Gerber and others, 1991). Three types of Jurassic plutonic rocks are common: mafic rocks, intermediate to silicic mixed or heterogeneous rocks, and leucocratic monzogranite (pl. 1). These plutons are difficult to date precisely, but appear to be largely160-165 Ma. Except in the Granite

Mountains, where Late Jurassic diorite is known (Young and others, 1992), the mafic rocks are generally the oldest and the leucocratic rocks the youngest. Other plutons possibly in the 160-165 Ma age group are in the Old Dad Mountains and Devils Playground area.

Compositionally, the mafic rocks include fine- to coarse-grained gabbro, diorite, and monzodiorite; common mafic minerals include clinopyroxene, hornblende, and biotite. Generally, the mafic rocks have SiO_2 contents of 49 to 55 percent; are subalkaline and metaluminous; and have relatively high abundances of large-ion lithophile elements (LILE), for example commonly as much as ≈ 3 percent K_2O and ≈1,000 ppm Ba. Young and others (1992) concluded from geochemical modelling that diorite evolved from parental magma that was derived from hydrous, REE-enriched subcontinental lithosphere and was contaminated by mafic granulite in the lower crust as it ascended to the upper crust.

The mixed intrusive rocks are by far the most abundant. They are markedly heterogeneous, ranging from fine-grained equigranular to coarsely porphyritic, and continuously from quartz monzodiorite to syenogranite and syenite. A number of phases or subgroups are present, typically bounded by gradational contacts. Chemically, the mixed intrusive rocks have a wide range of SiO_2 contents: 50 to 74 percent; they are subalkaline to, less commonly, alkaline; and metaluminous to weakly peraluminous. Some rocks are potassic, with K_2O/Na_2O as great as 2. Ba abundances are as great as 2,000 to 4,000 ppm in some of the mafic and intermediate rocks.

The leucocratic monzogranite is the most homogeneous of the three rock types. Whereas other plutonic phases grade complexly into one another, the monzogranite generally cleanly cross-cuts as the youngest phase. In the Colton Hills, it comprises medium- to coarse-grained, porphyritic leucocratic biotite monzogranite, locally with minor muscovite. It is subalkaline and generally moderately peraluminous. Trace-element abundances are unremarkable.

Many of the Jurassic plutonic rocks in the EMNSA are strongly altered. In the southern Providence Mountains and the southern Bristol Mountains, the rocks have undergone widespread albitization, characterized by replacement of potassium feldspar by albite (Miller and others, 1985; Fox, 1989; Fox and Miller, 1990). Intense albitization is present as white zones in otherwise normally mesotype rocks. Less intense albitization produces mottled patches or spots. Chemically, albitization is characterized by doubling of Na_2O content and nearly complete loss of K_2O: typically K_2O decreases from 6 percent to <1 percent. Accompanying changes in Fe, Mg, and Ca abundances depend on the extent of chloritization of mafic phases. Aluminum, Ti, Zr, Y, and REE are generally immobile on a hand-specimen scale during alteration. Alteration was probably mainly caused by repeated intrusion of magma into the shallow crust, creating large, long-lived hydrothermal systems.

Late Jurassic plutons in the EMNSA are known in the Granite and Ivanpah Mountains, but may be more widely present. Diorite in the Granite Mountains is ~155 Ma (Young and others, 1992). Other than its younger age, the diorite is similar to diorite in the Providence and Bristol Mountains. The Ivanpah Granite of Beckerman and others (1982) is 150 to 145 Ma (J.D. Walker, 1992, oral commun.). It consists of biotite monzogranite that is strongly porphyritic. The pluton is moderately peraluminous and potassic.

Late Jurassic Dikes

In the southern Providence Mountains, swarms of Middle to Late Jurassic intermediate to silicic dikes intrude Jurassic plutons (Miller and others, 1985). The dikes range from dacite porphyry to aphanitic rhyodacite to aplite. Similar intermediate dikes in the Colton Hills are intruded by Cretaceous plutons (Fox and Miller, 1990). Dikes in the Colton Hills have a minimum age of 146 Ma by K-Ar on biotite (D.M. Miller, 1984, unpubl. data). Similar dikes are known in a few other places within the EMNSA, such as the Cowhole Mountains. Possibly related swarms of Late Jurassic mafic or intermediate to silicic dikes are widespread in eastern California and southwestern Arizona (Chen and Moore, 1979; Hopson, 1988; Powell, 1981; Karish and others, 1987; Haxel and others, 1988; Tosdal and others, 1990). Some of the Jurassic dikes that crop out in the Providence Mountains were correlated by James (1989) with the approximately 150 Ma Independence dike swarm of eastern California. James (1989) suggested that the more than 500 km long dike swarm may be related to continental-scale arc-normal extension, changes in plate motions, or a combination of oblique subduction with left-lateral shear. The similar age of the Ivanpah Granite raises the possibility that plutons were also emplaced at the time of dike intrusion.

Cretaceous Plutonic Rocks

Most Cretaceous plutonic rocks of the EMNSA belong to the Early and Late Cretaceous Teutonia batholith (Beckerman and others, 1982). Beckerman and others (1982) considered the Teutonia batholith to be Jurassic and Cretaceous, based chiefly upon K-Ar cooling ages that provide minimum emplacement ages. They divided the batholith into seven plutons or units, with a large area of granitic rocks in the Halloran Hills area (DeWitt and others, 1984) undivided and undescribed (fig. 5). One pluton is Jurassic, the Ivanpah Granite (pl. 1). The other six plutons, which constitute most of the eastern batholith, are Cretaceous. Preliminary U-Pb zircon ages for major plutons of the batholith range from 93 to 100 Ma (determined by E. DeWitt, 1990). "Teutonia batholith" thus is hereby redefined to exclude the coincidentally spatially associated Jurassic Ivanpah Granite; this revised usage is followed in the summary below.

The six major plutons that constitute the eastern Teutonia batholith crop out chiefly in the New York Mountains, Mid Hills, and the Cima Dome-Wildcat Butte-Marl Mountains area (pl. 1). Five of the six plutons are fairly large, with exposed areas ≈50 to 200 km^2. These plutons are intermediate to felsic in composition. The sixth, mafic pluton forms a subcircular outcrop area ≈2 km in diameter; correlative bodies are yet smaller. Similar mafic to felsic rock units have been discerned in the Halloran Hills area (E. DeWitt and H.G. Wilshire, 1992, oral commun.)

The five relatively large plutons of the Teutonia batholith principally range in composition from quartz monzodiorite to syenogranite, with granodiorite and monzogranite as the principal compositional types; monzodiorite is a minor phase of one pluton. Despite this compositional range, granite constitutes most of the exposed rock. Quartz-poor modal compositions (quartz monzodiorite, quartz monzonite, quartz syenite) are present only in the Rock Spring Monzodiorite of Beckerman and others (1982). Other rocks are medium- to coarse-grained; some plutons or facies within plutons are equigranular, whereas others have alkali feldspar phenocrysts. Biotite is ubiquitous; hornblende is common to absent; the Kessler Springs pluton locally contains a little primary muscovite. Three of the five plutons are leucocratic--Teutonia Adamellite, Mid Hills Adamellite, and Kessler Springs Adamellite of Beckerman and others (1982)--with color indices less than 5 .

The sixth, small pluton (Black Canyon Hornblende Gabbro of Beckerman and others (1982), unit Kbc, pl. 1) comprises compositionally and texturally variable hornblende-rich mesotype to melanocratic gabbro. Magnetite content is high: average is 6.5 volume percent. This pluton intrudes two of the larger granitic plutons. Probable correlative bodies include one in Cedar Canyon and another, not shown on the map, near Wildcat Butte on Cima Dome.

Chemically, the six plutons of the Teutonia batholith form a broadly calcalkaline series (Beckerman and others, 1982). The hornblende gabbro contains 43 to 49 percent SiO_2; the other five plutons range from 68 to 77 percent SiO_2. The granitoid plutons generally straddle the boundary between metaluminous and peraluminous compositions. Moderately or strongly peraluminous granites are absent. Abundances of Ba, Sr, and Rb (the only trace elements analyzed) are generally normal and unremarkable for granitic rocks.

Geobarometric data indicate that the Rock Spring Monzodiorite of Beckerman and others (1982) was emplaced at pressures of <1 to 3 kb (Anderson and others, 1988; 1991), corresponding to upper-crustal depths of approximately <3 to 10 km. According to J.L. Anderson, (oral commun., 1990) present exposures provide a tilted view of the batholith: the shallowest plutons, emplaced at pressures of approximately 0.5 kb, are on the north and the deepest plutons, emplaced at approximately 3 kb, are to the south. However, these pressure data conflict with geologic evidence that the roof of the batholith is exposed in the south (Goldfarb and others, 1988) as a shallowly south-dipping surface in the Providence and Marl Mountains; the south should therefore be the shallowest part of the batholith. The Teutonia batholith is among the shallowest of the Mesozoic plutonic complexes in the Mojave Desert region studied by Anderson and others (1988, 1991): pressure estimates for ten other complexes range from 2 to 9 kb.

Small, shallow-level stocks that lie northeast of the Teutonia batholith appear to represent outliers of the magmatic belt in earliest Late Cretaceous time. Magmatic alteration, intrusive breccia, and felsite dikes in the Colosseum mine area of the Clark Mountains (described in a later section) are about 100 Ma (Sharp, 1984). Similar alteration and breccia, as well as small hypabyssal bodies of biotite granodiorite, lie about 5 km northeast of the EMNSA in the New York Mountains, near Crescent Peak (Miller and Wooden, 1993). This granodiorite yielded a 94.4 ± 2.4 Ma K-Ar biotite date.

Latest Cretaceous plutons in the EMNSA range from 75 to 70 Ma (Howard and others, 1987; Fox and Miller, 1990, citing J.L. Wooden, oral commun., 1987). Known ~70-Ma Late Cretaceous plutons crop out in the Granite Mountains and at Homer Mountain; probable Late Cretaceous plutons crop out in the Fenner Hills and near Bobcat Hill. In the Granite Mountains, a suite of Cretaceous igneous rocks includes a granodiorite pluton, a zoned pluton, and granite, aplite and pegmatite dikes (Howard and others, 1987). The granodiorite pluton makes up most of the western Granite Mountains (pl. 1), and a larger zoned pluton makes up the southeastern part (Howard and others, 1987) and part of the adjacent Providence Mountains (Miller and others, 1985). Magmatic biotite from the zoned pluton yielded K-Ar dates, possibly emplacement ages, of 70.9 to 74.5 Ma (Miller and others, 1985; Howard and others, 1987). In general, latest Cretaceous plutonic rocks are silicic, slightly to strongly peraluminous granites.

Mesozoic deformation

Some Mesozoic deformational features of regional extent crop out in the western and north-central parts of the EMNSA. These deformational features are reflections of shortening shown by brittle-style thrust plates developed in the foreland of the Cordilleran thrust belt and ductile-style nappes in southeastern California and Arizona (Burchfiel and Davis, 1971, 1977, 1981; Howard and others, 1980; Snoke and Miller, 1988; Miller and Barton, 1990).

Generally east-directed thrust faults, present in the Cowhole Mountains and the Clark Mountain Range areas, may be Middle Triassic(?) through Early Jurassic (Burchfiel and Davis, 1981). In the Cowhole Mountains, metamorphosed Paleozoic rocks were interpreted as having been thrust eastward and then overlapped unconformably by the Lower Jurassic Aztec Sandstone. However, Busby-Spera (1988) and Busby-Spera and others (1989) presented evidence that the sandstone is Middle Jurassic and may overlie a normal, not thrust, fault. In the Clark Mountain Range, some east-directed thrust faults were cut by small dioritic plutons originally dated at 190 and 200 Ma by K-Ar (Burchfiel and Davis, 1981) but now known as Late Jurassic. Latest Early Cretaceous thrusting there placed Paleozoic strata over the Early Cretaceous Delfonte volcanic rocks. This thrust was then intruded by plutons of the mid-Cretaceous Teutonia batholith (Burchfiel and Davis, 1971, 1981; Fleck and others, in press). A similar sequence of faulting, although not as well constrained by dated rock bodies, holds in the New York Mountains.

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