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Paleogeographic and tectonic implications of Jurassic sedimentary and volcanic sequences in the central Mojave block

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ABSTRACT

Sedimentologic, stratigraphic, and geochronologic data from strata of early Mesozoic age in the central Mojave block elucidate the paleogeographic and tectonic evolution of the magmatic arc in the southern U.S. Cordillera. A sequence of calcareous siltstone, volcaniclastic conglomerate, tuff, and quartzose sandstone records the transition from shallow-marine rocks of the Fairview Valley Formation to the subaerial Sidewinder volcanic series. Quartzose sandstones occur below, within, and above the transitional sequence and indicate that texturally mature, craton-derived quartz sand gained access to the arc during the initial stages of volcanism. U-Pb data indicate that explosive volcanism began at 179.5 ± 3.0 Ma and continued until 151 ± 1.3 Ma (Lower Sidewinder volcanic series). A rhyolite dike of the Independence dike swarm (Upper Sidewinder volcanic series) that postdates normal faulting and tilting of the ignimbrites yielded a U-Pb date of 151.9 ± 5.6 Ma. The data define the age of extension and development of the angular unconformity between the Upper and Lower Sidewinder volcanic series at ca. 151 Ma.

The data suggest that at least part, and possibly all, of the Fairview Valley Formation is late Early Jurassic in age. We correlate the Fairview Valley Formation with Mesozoic metasedimentary rocks in the Rodman Mountains and Fry Mountains, and at Cave Mountain to the east. Eolian quartz arenites in these sequences suggest a coastal environment coeval with the Navajo Sandstone on the Colorado Plateau. The reinterpretation of the shallow-marine rocks as Jurassic instead of Triassic suggests a period of uplift and erosion or nondeposition extending from the Early Triassic into the Early Jurassic, followed by a return to marine conditions. Shallow-marine conditions persisted until the beginning of arc volcanism in the late Early Jurassic time. Similarities to the early Mesozoic arc of the Sierra Nevada, together with the structural evolution of the region, suggest that the change from high-standing to low-standing paleogeography reflects a large-scale tectonic control on relative sea level related to a period of intra-arc extension or transtension.

Schermer, E.R., Busby, C.J., and Mattinson, J.M., 2002, Paleogeographic and tectonic implications of Jurassic sedimentary and volcanic sequences in the central Mojave block, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., eds., Geologic Evolution of the Mojave Desert and Southwestern Basin and Range: Boulder, Colorado, Geological Society of America Memoir 195, p. 93–115.

INTRODUCTION

Understanding of the paleogeography and tectonic evolution of the early stages of the continental-margin magmatic arc in the southern U.S. Cordillera has been hampered by incomplete knowledge of the ages and depositional environments of sedimentary and volcanic rocks in the greater Mojave Desert region (e.g., Glazner et al., 1994). In the central Mojave block, well-preserved volcanic and sedimentary sequences record the initiation of arc volcanism and provide insight into the paleogeography of the early arc. In this study we present sedimentologic, stratigraphic, and U-Pb geochronologic data on the Fairview Valley Formation and the overlying Sidewinder volcanic series, a sedimentary and volcanic sequence of early Mesozoic age exposed in the Victorville area of the Mojave block (Fig. 1). Our results suggest new correlations of lower Mesozoic sequences across the Mojave block and a revised interpretation of the paleogeographic evolution of the region. Our new U-Pb ages also define the duration of explosive volcanism and set limits on the ages of intra-arc deformational events. Inasmuch as direct dating of specific structures has been difficult, we also attempt to relate the style of intra-arc sedimentation and magmatism to the tectonic setting.

GEOLOGIC SETTING

The Mesozoic magmatic arc in the Mojave Desert was built across Precambrian–Paleozoic cratonal-miogeoclinal strata that were deformed and metamorphosed in Pennsylvanian–Triassic time, possibly during strike-slip truncation of the continental margin (Burchfiel and Davis, 1972, 1981; Miller and Cameron, 1982; Stone and Stevens, 1988; Walker, 1988; Martin and Walker, 1995). Permian or Early Triassic alkalic plutonic rocks intrude deformed Paleozoic strata and record the initiation of subduction-related magmatism (Barth et al., 1990; C. Miller, 1978; Miller, 1978b; Miller et al., 1995). Shallow-marine rocks that unconformably overlie the Paleozoic rocks have been interpreted as a Lower Triassic overlap assemblage deposited across the deformed margin from the Victorville region to Cave Mountain (Fig. 1) and across undeformed rocks farther east (Walker, 1987, 1988). Facies boundaries within the overlap sequence strike northwest, indicating that the change in trend of the continental margin from northeast prior to the truncation event to northwest afterward was accomplished by Early Triassic time (Walker, 1988). The shallow-marine rocks are typically overlain by thick sequences of volcanic rocks that reflect the transition to the tectonics of the fully active magmatic arc. In several areas, including the Victorville region, Cave Mountain, and the Soda Mountains (Fig. 1), quartzite and quartz-rich sandstone occur between and are locally interfingered with the shallow-marine rocks and the volcanic rocks. The age of the quartzose sandstones has been somewhat controversial, and some exposures have been considered Triassic whereas others have been interpreted as Jurassic in age (e.g., Walker, 1987). Jurassic and Cretaceous batholithic rocks intrude the supracrustal rocks and are widely exposed throughout the Mojave Desert (Fig. 1).

The shallow-marine Fairview Valley Formation (Bowen, 1954; Dibblee, 1960a, 1960b; Miller, 1978b, 1981) forms part of Walker's (1988) overlap assemblage in the Victorville region (Fig. 2) and was interpreted to be Early Triassic in age. Coarse conglomeratic units within the Fairview Valley Formation were interpreted by Miller (1978b, 1981) as alluvial-fan facies reflecting intra-orogenic deposition following a Permian–Triassic orogenic event. Quartzose sandstone overlies the shallow-marine rocks and the conglomerate. The contact of the Fairview Valley Formation and the quartzose sandstone with overlying volcanic rocks is parallel to bedding in the underlying strata across the region and appears to be conformable.

An important aspect of early Mesozoic arc paleogeography is reflected in the observed association of quartzose sandstones and volcanic rocks in the early Mesozoic arc. Busby-Spera (1988) noted that supermature eolian quartz arenites are commonly associated with proximal volcanic rocks throughout the southwestern Cordillera, and she interpreted the association to reflect trapping of eolianites in a low-standing arc graben-depression. The eolianites were correlated by earlier workers with the Lower Jurassic Navajo Sandstone of the Colorado Plateau and the Aztec Sandstone of the Las Vegas region (Cameron et al., 1979; Hewett, 1931, 1954; Marzolf, 1980, 1983; Miller and Carr, 1978). More recent work (Busby-Spera, 1988; Busby-Spera et al., 1990; Fackler-Adams et al., 1997; Riggs et al., 1993) has indicated that some eolianites intercalated with arc-type volcanic rocks are age-equivalent to several younger quartz arenites of the Colorado Plateau, including the Middle Jurassic Temple Cap and Page Sandstones and the upper Middle Jurassic Carmel Formation. Quartzites and quartz-rich sandstones also occur in sequences interpreted by Walker (1987, 1988) to be Early Triassic in age, but most of these occurrences are too metamorphosed to determine whether they were deposited in an eolian environment. To understand the paleogeography of coeval backarc and arc environments and to determine whether deformation events in the arc are related to those in the backarc, better understanding of the ages and depositional environments of these quartzose strata is required (e.g., Bjerrum and Dorsey, 1995; Burchfiel and Davis, 1981; Lawton, 1994).

Most of the pre-Tertiary volcanic rocks in the Mojave Desert are silicic and intermediate-composition rocks of Jurassic age. The largest exposure, the Sidewinder volcanic series (Bowen, 1954) (Figs. 1, 2, 3), consists of a >4-km-thick sequence of Jurassic rhyolitic to dacitic intracaldera ignimbrites (Lower Sidewinder volcanic series) overlain with angular unconformity by a thin sequence of rhyolite to basalt lavas (Upper Sidewinder volcanic series); (Karish et al., 1987; Schermer and Busby, 1994). Recent dating of ignimbrites and lavas in the Cowhole Mountains at 172 $\pm$ 6 to 167 $\pm$ 4 Ma defines the age of magmatism in that region as Middle Jurassic (Busby-Spera et al., 1989; Busby et al., this volume). Dating of the

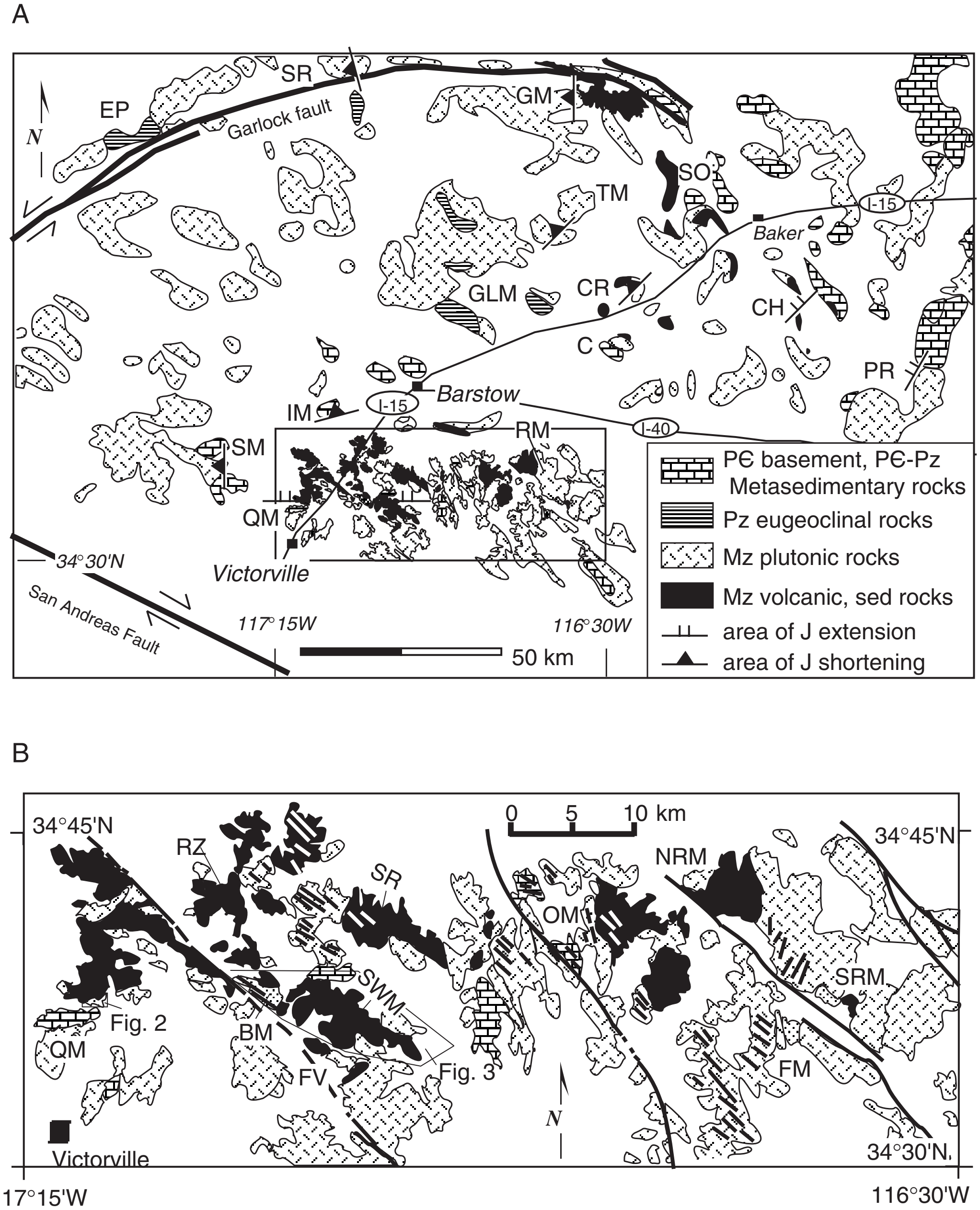


Figure 1. (A) Generalized geologic map of the western Mojave Desert, showing Mesozoic supracrustal and plutonic rocks, pre-Mesozoic strata, and localities mentioned in text. Abbreviations: C—Cave Mountain, CH—Cowhole Mountains, CR—Cronese Hills, EP—El Paso Mountains, GLM—Goldstone-Lane Mountain, GM—Granite Mountains, IM—Iron Mountain, PR—Providence Mountains, QM—Quartzite Mountain, RM—Rodman Mountains, SM—Shadow Mountains, SO—Soda Mountains, SR—Slate Range, TM—Tiefort Mountains. Box outlines study area. After Martin and Walker (1991). (B) Location map of areas containing Sidewinder volcanic series: BM—Black Mountain, FM—Fry Mountains, FV—Fairview Valley, NRM—Northern Rodman Mountains, OM—Ord Mountain, QM—Quartzite Mountains, RZ—Ritz Mountain, SR—Stoddard Ridge, SRM—Southern Rodman Mountains, SWM—Sidewinder Mountain. Short bold black and white lines indicate Independence dike swarm, light shading indicates location of Aztec Sandstone. After Karish et al. (1987).

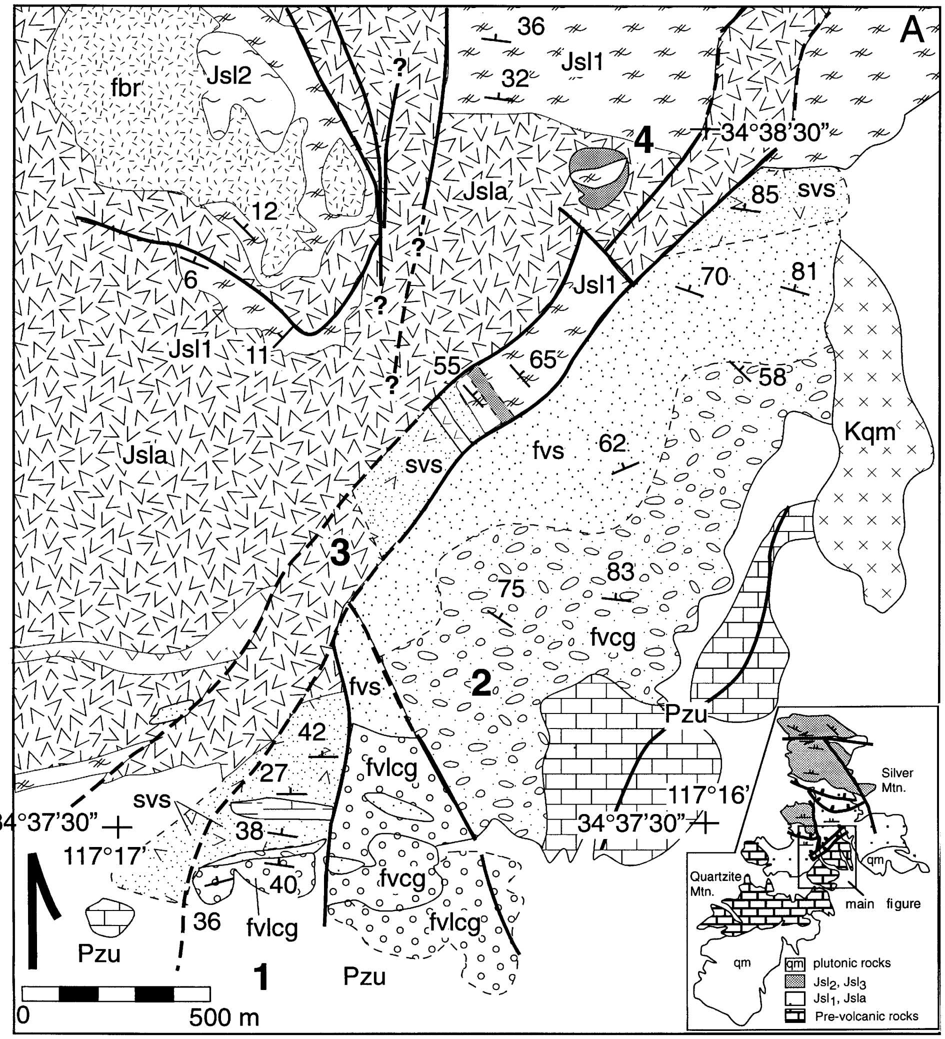


Figure 2. (A) Geologic map of northern Quartzite Mountain showing contact between the Fairview Valley Formation and the Sidewinder volcanic series. Bold numbers 1–4 refer to fault blocks and stratigraphic columns in B; map units are explained in C except for the following: fbr—Jurassic? hypabyssal rhyolite, Kqm—Cretaceous quartz monzonite, Pzu—undifferentiated Paleozoic rocks. Structural symbols show strike and dip direction of bedding in sedimentary units and compacted pumice foliation in ignimbrites. Inset shows generalized geology of Quartzite Mountain area; bold lines are faults, with ticks showing dip direction of normal faults. (B) Stratigraphic columns showing gradational contact between Fairview Valley Formation and Sidewinder volcanic series. Thicknesses are approximate owing to poor exposure, and except for column 1 (that section was paced), are estimated from mapped extents of units. (C) Diagram showing inferred lithofacies correlation of units in A and B. Unit descriptions are in Table 1.

Dome Rock sequence in the Palen Mountains indicates that volcanism spanned 174 ± 8 to 155 ± 8 Ma (Fackler-Adams et al., 1997). Permian basaltic and andesitic volcanic rocks are present in eugeoclinal assemblages in the El Paso Mountains and the Goldstone–Lane Mountain region (Miller and Sutter, 1982; Carr et al., 1984).

One of the major controversies in the interpretation of the Mesozoic tectonic setting of the southwestern Cordillera has been whether the tectonic regime was contractional, neutral, or extensional during the early evolution of the magmatic arc (e.g., Burchfiel and Davis, 1981; Karish et al., 1987; Busby-Spera, 1988; Walker et al., 1990a). Contrasting interpretations have been proposed not only for different time frames but also for different segments of the arc and backarc during the same time frame. The volcanic sequences have been affected by thrusting, folding, and normal faulting in different areas (e.g., Schermer, 1993; Saleeby and Busby-Spera, 1992, and references therein); therefore, obtaining radiometric ages for the volcanic rocks helps to define the duration of volcanism and the ages of deformational events.

THE FAIRVIEW VALLEY FORMATION AND CONTACT RELATIONSHIPS WITH THE SIDEWINDER VOLCANIC SERIES

We used the maps, stratigraphic descriptions, and facies analysis of E. Miller (1978a, 1978b, 1981) and Schermer and Busby (1994) as a basis for detailed examination of the sedimentology and stratigraphy of the Fairview Valley Formation and Sidewinder volcanic series. In this section we describe the upper Fairview Valley Formation and the lowermost Sidewinder volcanic series and the nature of the contact between the two sequences at each occurrence in the central Mojave block. We have not studied the lower part of the Fairview Valley Formation in detail and have relied on descriptions and interpretations of Miller (1978a, 1978b, 1981) and Walker (1987). We interpret the data in terms of depositional environments, propose new correlations with other exposures in the eastern Mojave block and discuss the tectonic and paleogeographic implications of these interpretations. The time scale used is that of Gradstein et al. (1994), with revisions to the Permian-Triassic

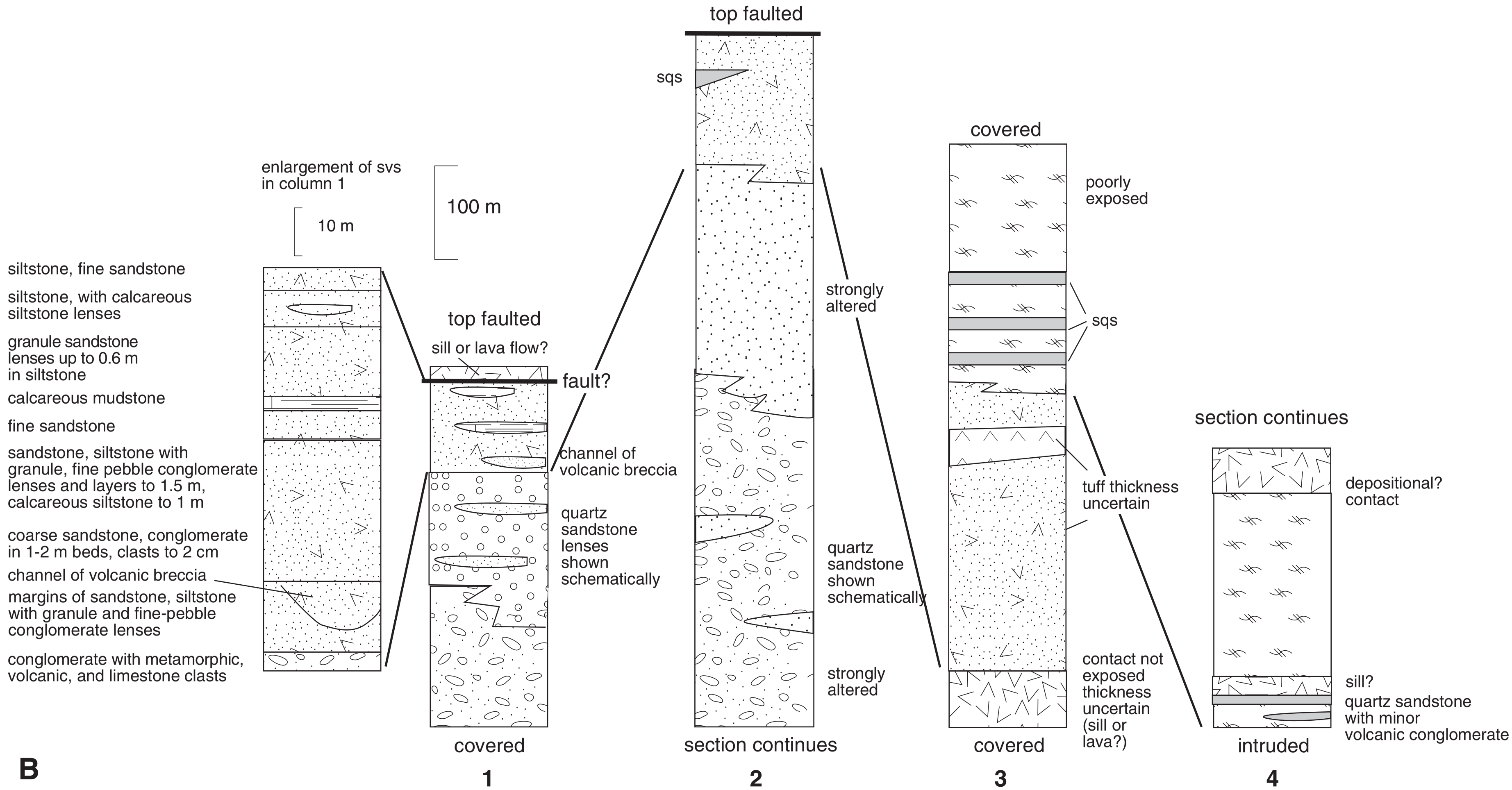
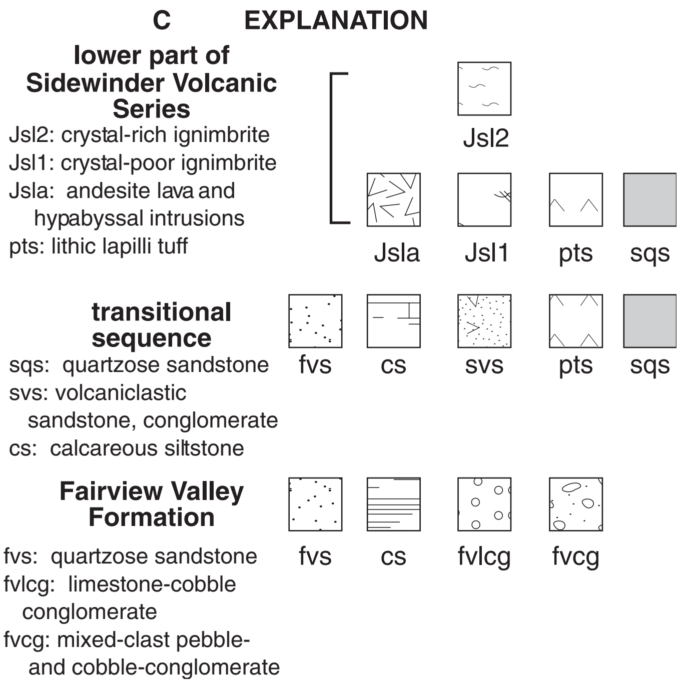


Figure 2. Continued



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boundary and Middle Triassic time scales as reported by Bowring et al. (1998) and Mundil et al. (1996), respectively.

Previous work

The Fairview Valley Formation was named and first described by Bowen (1954). Miller (1978a, 1978b, 1981) studied the formation in detail at several locations in the Victorville region and described a sequence of calc-silicate hornfels, silty limestone, calcareous siltstone, and conglomerate overlain by quartzite and rocks of the Sidewinder volcanic series. The contact between the Fairview Valley Formation and overlying rocks has been variably interpreted as unconformable (Miller, 1978b, 1981) or conformable (Walker, 1987).

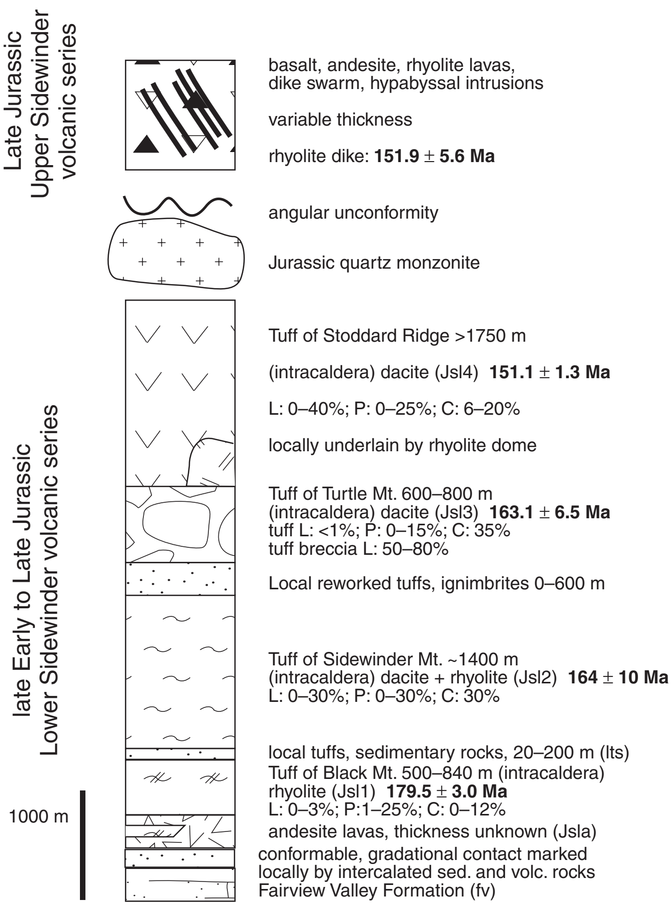
Interpretation of the age and depositional environment of the Fairview Valley Formation has been hampered by a lack of fossils and by low-grade metamorphism and deformation. Miller (1978a, 1978b, 1981) interpreted sedimentary structures such as small-scale herringbone cross-stratification, burrows, and mudcracks to indicate either a shallow-marine or a lacustrine setting for finer-grained parts of the sequence and an alluvial-fan setting for limestone-cobble conglomerates exposed at Black Mountain and Sidewinder Mountain (Fig. 3B). Walker (1987, 1988) correlated the sequence at Black Mountain with similar, better-preserved Lower Triassic sequences in other parts of the Mojave Desert, e.g., the Soda Mountains (Fig. 1). He interpreted the presence of conodonts, in addition to the sedimentary structures indicative of shallow-water deposition, to reflect a marginal-marine environment. One of the limestone beds sampled by Walker (1987), however, contains a mixed fauna of Permian and Triassic age, indicating that at least some of the conodonts are reworked, and thus the interpretations of marine setting and an Early Triassic age remain uncertain. A monzonite pluton, unconformably overlain by the Fairview Valley Formation at Black Mountain, has been dated by U-Pb at 243 ± 2 Ma (Miller et al., 1995); the age of this pluton also suggests that the formation must be younger than Early Triassic.

New results

At Quartzite Mountain, Black Mountain, and Sidewinder Mountain (Figs. 2, 3), we interpret the Sidewinder volcanic series to lie conformably above the Fairview Valley Formation, and we show that both units contain quartz-rich sandstones. At Quartzite Mountain, a gradational contact records the transition between the Fairview Valley Formation and the Sidewinder volcanic series (Fig. 2). The stratigraphic sequences at Black Mountain, Sidewinder Mountain, and other areas to the east (Figs. 3, 4) provide additional facies characteristics and age constraints. The Fairview Valley Formation and the Sidewinder volcanic series are variably deformed, hydrothermally altered, and contact metamorphosed. Because sedimentary structures, textures, and compositions are typically visible despite the alteration, we omit the prefix "meta-" in our descriptions herein; however, we note particular locations where alteration is so intense as to hamper sedimentologic interpretation.

Quartzite Mountain. A newly identified transitional sequence between the Fairview Valley Formation and the Sidewinder volcanic series at Quartzite Mountain reveals that the contact is gradational. Miller (1978a, 1978b, 1981), in contrast, interpreted the Fairview Valley–Sidewinder contact there as an angular unconformity. Further mapping establishes that the contact is a fault at localities where there is an angular discordance, but is depositional at other localities (Fig. 2A). The Fairview Valley Formation at Quartzite Mountain consists of ≥1000 m of conglomerate (Miller, 1978a, 1978b, 1981). The transitional sequence comprises four lithologic units: (1) volcaniclastic sandstone and conglomerate (svs), (2) lower quartzose sandstone (fvs), (3) calcareous siltstone (cs), and (4) upper quartzose sandstone (sqs) (see Fig. 2 and Table 1) (all four units were combined as unit sws1 by Schermer and Busby, 1994). Contacts between most of the units are poorly exposed, but generally parallel the bedding within each fault block.

Correlation of stratigraphy between the various fault blocks at Quartzite Mountain provides a composite link between the Fairview Valley Formation and the Sidewinder volcanic series. The map and stratigraphic columns in Figure 2 show the transition from calcareous siltstone (cs), quartzose sandstone (fvs), and conglomerate (fvcg, fvlcg) typical of the Fairview Valley Formation upward into increasing proportions of fine- to medium-grained quartzose sandstone (sqs) and interbedded volcaniclastic sandstone and conglomerate (svs), intermediate-



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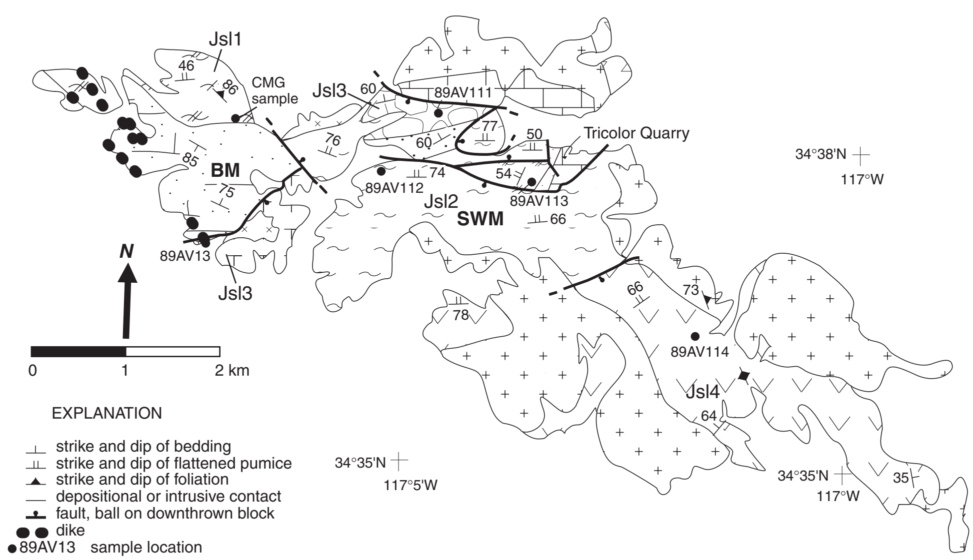

B

Figure 3. (A) Generalized stratigraphic column of the Sidewinder volcanic series showing units dated in this study. Compositions indicated by percentage ranges of lithic lapilli (L), pumice lapilli (P), and crystal content (C) from entire study area. (B) Simplified geologic map of Sidewinder (SWM) and Black (BM) Mountains showing location of samples dated, modified from Schermer and Busby (1994). Sample data listed in Table 2. CMG = sample from Graubard et al. (1988).

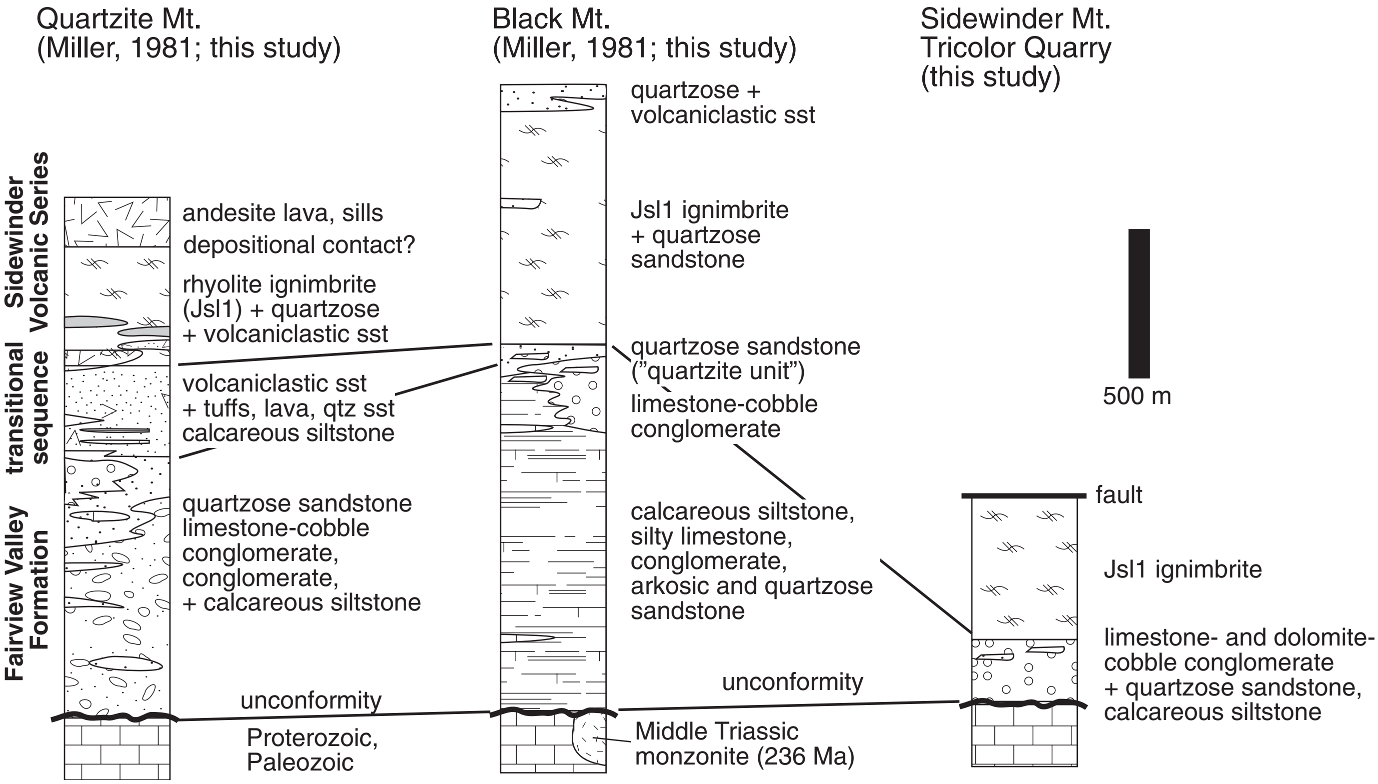

Figure 4. Stratigraphic columns showing characteristics of Fairview Valley Formation–Sidewinder volcanic series contact at Quartzite Mountain, Black Mountain, and the Tricolor Quarry area of Sidewinder Mountain.

composition tuffs (pts), and andesite lava (Jsla). Descriptions are given in Table 1. The stratigraphically lowest exposures of the Fairview Valley Formation at Quartzite Mountain are pebble and cobble conglomerates (fvcg). These conglomerates are locally interbedded with and overlain by limestone-cobble conglomerate (fvlcg); clasts in both types of conglomerate were derived from Paleozoic units (Miller, 1978b, 1981). Both types of conglomerate contain lenses of quartzose sandstone (unit fvs), and locally a thick section dominated by this sandstone overlies the conglomerate section (e.g., Fig. 2B, column 2). The quartzose sandstones and siltstones contain well-rounded monocrystalline quartz grains and little or no polycrystalline quartz or quartzite lithic fragments. Similar quartzose sandstones (unit sqs) occur stratigraphically higher, intercalated with the volcaniclastic units (Fig. 2B, column 2) and with basal lavas, tuffs, and ignimbrite (Jsl1) of the Sidewinder volcanic series (Fig. 2B, columns 3, 4). These stratigraphically higher quartzose sandstones contain fine- to medium-grained well-rounded quartz grains in addition to volcanic material. The volcaniclastic units (svs) contain porphyritic and aphyric rhyolitic to andesitic clasts in an altered, sandy to silty matrix.

Although the transitional sequence is faulted, we are able to correlate upper parts of the sequence in the southern fault blocks (Fig. 2B, columns 1, 2) with the lower parts of the sequence in the northern fault blocks (Fig. 2B, columns 3, 4). The fault blocks that contain the basal Sidewinder volcanic series (Fig. 2B, columns 3, 4) comprise ignimbrites, tuffs, and lavas intercalated with volcaniclastic and quartzose sandstone beds whose compositions and sedimentary structures are similar to those in lower parts of the sequence where no primary volcanic rocks are present. The ignimbrites occur in thin (2–15-m-thick) layers that are weakly to moderately welded and are interpreted to be outflow sheets from a caldera located near or at Black Mountain (Schermer and Busby, 1994).

The composition of the sedimentary units from the upper part of the Fairview Valley Formation upward through the transitional sequence records a continual supply of texturally mature quartz sand in combination with other, more local, sources. The contrast in texture between the uniformly sized, well-rounded quartz grains with the wide grain-size range and angular to subangular nature of the clasts of the volcanic material suggests two distinct sources. Both quartzose sandstones (Fairview Valley unit fvs and transitional sequence unit sqs) contain a population of the texturally mature grains, suggesting that the quartz-sand source persisted during the initial stages of volcanism. Texturally mature quartz sandstones in other parts of the Mojave Desert have been interpreted to be derived from cratonal eolian sources (e.g., Miller and Carr, 1978; Busby-Spera, 1988), and we concur with this interpretation for the quartzose sandstones at Quartzite Mountain.

TABLE 1. LITHOLOGIC DESCRIPTIONS FOR ROCKS AT QUARTZITE MOUNTAIN*

Unit	Outcrop Description	Composition
Jsl2	CRYSTAL RICH IGNIMBRITE*	Rhyolite to dacite, complexly zoned. Crystals avg. 30%, include coarse K-feldspar, quartz, biotite. Lithics (silicic volcanics) rare, pumice sparse
Jsl1	CRYSTAL POOR IGNIMBRITE*	Rhyolite; crystals avg. <10–12%; lithics 0–3% (silicic and mafic volcanics, calc-silicate rock, marble, quartzite); pumice 1–25%
Jsla	ANDESITE LAVA AND HYPABYSSAL INTRUSIONS*	Andesite; phenocrysts avg. 30–35%, include plagioclase and pyroxene, groundmass typically recrystallized, altered
pts†	LITHIC LAPILLI TUFF in part may grade laterally into Jsla	Andesite or dacite with up to 15% volcanic lithics, 20–45% crystals including plagioclase, biotite, Fe-oxides
svsß	VOLCANICLASTIC SANDSTONE, CONGLOMERATE 1. Med. to cse gr. volcanic-lithic sst, siltst., rare thing tuff? or mudst. laminae 2mm thick. Thin-bedded (0.2–1 cm) with indistinct planar, rare low-angle cross strat. 2. Volcanic-lithic granule, pbl sst with clasts 0.2–1 cm; lenses 20–60 cm thick, locally to 2m. 3. Volcanic breccia, matrix-supported med-thick bedded, crudely stratified, nongraded or normally graded, rare scour/fill; angular to subangular volcanic clasts; subangular to subrounded metamorphic clasts 1–10 cm, rarely to 25 cm.	Clasts include intermed. comp. plag. porphyry, silicic porphyritic and aphyric volc. clasts, quartzite, marble, siltst, rare gneiss and granite. Metamorphic clasts generally <15% of clasts. matrix is altered, sandy to silty, composed of clay and/or white mica, fine quartz and feldspar grains, epidote, and altered biotite.
sqsß	QUARTZOSE SANDSTONE Fine-med gr. planar laminated, thin bedded; indistinct bedding and grain size where altered.	Fine to medium-grained well-rounded quartz grains, angular feldspar grains, and minor rounded to subrounded plutonic clasts and polycrystalline quartz. Matrix of sericite, quartz, and Fe-oxides may represent altered volcanic material.
csß	CALCEROUS SILTSTONE Parallel-laminated, beds 0.2–1 cm, intercalated with volcanic lithic sst in beds, lenses up to 60 cm.	Fine-grained quartz, epidote, calcite, white mica.
fvs	QUARTZOSE SANDSTONE Fine-med gr, planar laminated. Typically extremely altered.	Contains well-rounded quartz grains in altered matrix, quartzite lithics.
fvlcg	LIMESTONE COBBLE CONGLOMERATE Massive to crudely stratified	Limestone, dolomite clasts in silty limestone matrix.
fvcg	MIXED PEBBLE, COBBLE CONGLOMERATE Massive to crudely strat. cgl with metamorphic, rare volc and limestone clasts in altered calcerous? sst matrix. Local quartzose and metacalc sst, siltst. lenses. Typically strongly altered.	Abundant metasedimentary and gneiss clasts derived from underlying Paleozoic and Precambrian units, lesser monzonitic to granitic clasts, and minor volcanic clasts. Matrix contains carbonate, quartz, feldspar, chert, and volcanic debris (Miller, 1978a).

*Descriptions of units in other areas and detailed descriptions and point counts of all Sidewinder volcanic units, are given in Schermer and Busby (1994).
†Included in unit lts of Schermer and Busby (1994).
ß Included in unit sws1 of Schermer and Busby (1994).

Volcanic detritus is abundant in the transitional sequence. The volcanic lithic conglomerates in unit svs contain clasts that resemble, in phenocryst composition and abundance, the andesite lavas and shallow intrusions (Jsla) interpreted to overlie and intrude the volcaniclastic sequence and possibly interfinger with it (Fig. 2B, columns 1, 3). The conglomerates also contain abundant silicic volcanic clasts that cannot be positively identified as derived from part of the Sidewinder volcanic series, but are similar in composition and texture to porphyritic rhyolite in adjacent ranges described by Schermer and Busby (1994). Upper stratigraphic levels of the volcaniclastic unit (svs) are interlayered with primary volcanic rocks (pts, Jsl1; Fig. 2B, column 3). Metamorphic and rare limestone clasts represent <15% of the clasts in the conglomerates of unit svs and are typically more rounded than the volcanic clasts. Sandstones in the unit also contain plutonic lithic grains that appear similar to those in unit fvcg. The metamorphic and plutonic clast types are identical to those found in lower parts of the Fairview Valley Formation.

Sedimentary structures and textures are locally well preserved in the volcaniclastic part of the sequence in the west (Fig. 2B, column 1), whereas in other fault blocks (columns 2, 3), poor exposures and hydrothermal alteration hinder interpretation of the depositional environments. Matrix-supported conglomerate and coarse-sand layers locally exhibit crude stratification and normal grading. In fault block 1, a channel ≥15 m wide and ~10–15 m deep is filled with volcanic-lithic breccias and medium- to coarse-grained sandstones. These form an upward-thinning and -fining sequence of beds; the proportion of sandstone lenses (as opposed to conglomerate) increases upward, and siltstone beds up to 2 m thick fill the top of the channel. The channel appears to be faulted on its eastern margin, but is bounded on its western margin by a sequence of siltstone and fine-grained sandstone with thin granule sandstone lenses that also overlie the channel. The strata above the channel become finer grained up section as shown by increasing amounts of planar-laminated, thin-bedded calcareous siltstone and mudstone with rare low-angle cross-lamination. Possible tuff layers 1–3 mm thick are altered to sericite.

The volcaniclastic sedimentary rocks appear to have been deposited in a subaqueous environment. The predominance of fine-grained parallel-laminated deposits outside the channel-filling sequence suggests a quiet-water setting. The grading and crude stratification in the coarse-grained deposits suggest deposition from high-density turbidity currents and/or dilute debris flows; the general absence of cross-bedding and scour-and-fill structure argues against fluvial deposition. We interpret this sequence to represent gravity flows having a high concentration of sediment shed from nearby volcanic sources into a quiet-water setting that apparently records the latest stages of Fairview Valley Formation shallow-marine or lacustrine deposition.

Black Mountain. The Fairview Valley Formation at Black Mountain (Figs. 3, 4), its type locality, consists of >1200 m of conglomerate, silty limestone, and calcareous siltstone and sandstone (Bowen, 1954; Miller, 1978a, 1978b, 1981). Above the basal unconformity, marked by a conglomerate with monzonite clasts, the sequence is dominated by fine-grained calcareous rocks interpreted to have been deposited in a shallow-marine or lacustrine environment (Miller, 1978b; Walker, 1987). The sequence also contains thin conglomerate lenses in the lower part with clasts of marble, monzonite, and rare rhyolite, granite, quartzite, chert, limestone, and gneiss (Miller, 1981). A 675-m-thick conglomerate in the upper part of the formation contains cobble- to boulder-sized clasts of Paleozoic limestone and is generally unsorted, with thick to massive beds. Miller (1978a, 1978b, 1981) interpreted these characteristics to reflect an alluvial-fan setting; however, because the conglomerate interfingers westward with limestones and calc-silicates interpreted to have been deposited subaqueously, we suggest that "fan delta" is a better term for this paleo–depositional environment.

The nature of the contact between the Fairview Valley Formation and Sidewinder volcanic series at Black Mountain differs from that to the west at Quartzite Mountain. Miller (1978a, 1978b, 1981) interpreted the Fairview Valley Formation at Black Mountain to be overlain along an erosional unconformity by a distinct "quartzite unit" (Miller's term) that is conformably overlain by rocks of the Sidewinder volcanic series. Miller's interpretation of an unconformable contact between the quartzite unit and the Fairview Valley Formation was based on the observations that (1) the quartzite unit overlapped contrasting facies (conglomerate and calcareous siltstone-sandstone) in the Fairview Valley Formation (Fig. 4) and (2) the quartzite unit, composed of 50%–90% fine-sand-sized quartz grains in a matrix of calc-silicate minerals, was mineralogically distinct from arkosic sandstones in the Fairview Valley Formation.

Our new results confirm the alternative interpretation of Walker (1987) that the quartzite unit is part of the upper Fairview Valley Formation and records an increase in the supply of quartz sand to the basin. Miller (1978a, 1978b) interpreted the calc-silicate matrix as altered volcanic material, but we have found no evidence for relict volcanic crystals or other volcanic debris; we therefore reinterpret the matrix as altered calcareous siltstone, similar to calcareous siltstones that occur throughout the Fairview Valley Formation at Black Mountain. Further evidence for a gradational contact at the base of the quartzite unit includes the following: (1) The matrix of the carbonate-clast conglomerate is rich in quartz sand in at least the upper 15–20 m of the conglomerate facies. (2) Beds of quartzose sandstone averaging ~1 m thick are intercalated in the upper ~75 m of the conglomerate. (3) A similar upward increase in the abundance of quartzose sandstone relative to limestone and calcareous siltstone occurs in the sandstone-siltstone facies west of the conglomerate. (4) Limestone-clast conglomerate lenses up to 1 m thick occur within what Miller (1978a, 1981) mapped as the quartzite unit. (5) Bedding is subparallel above, within, and below the quartzite unit, as also noted by Miller (1978, 1981; Fig. 4). An interpretation of a gradational contact between the quartzite unit and the Fairview Valley Formation at Black Mountain is also consistent with the upward increase in quartzose sandstone observed in the Fairview Valley Formation at Quartzite Mountain.

At Black Mountain, quartzose sandstone also occurs interstratified with the lowest volcanic strata of the Sidewinder volcanic series, similar to the sequence at Quartzite Mountain. Miller (1978a, 1981) and Walker (1987) interpreted the Sidewinder volcanic series to conformably overlie the quartzite unit and noted the similarity of the sandstones above and below the contact, and we agree with this interpretation. Graubard et al. (1988) interpreted the contact at the base of the volcanic rocks as a fault; further mapping indicates that this fault reflects local shearing along a predominantly depositional contact. Quartzose sandstone containing a mixture of angular and well-rounded fine-sand-sized quartz grains occurs within and at the top of the first ignimbrite unit (Jsl1, Fig. 3, 4) at Black Mountain. Schermer and Busby (1994) interpreted the ignimbrite to represent one caldera-forming eruption, although distinct flow units were recognized on the basis of variations in abundance of pumice lapilli. The quartzose sandstone unit within the ignimbrite is a lens <20 m thick, has bedding subparallel to compacted pumice foliation, is intercalated with laminated (reworked?) tuffs, and shows no evidence of brecciation or disruption that would be expected if the sandstone was derived from caldera-rim landslides; thus we interpret it to have been deposited during a brief(?) hiatus in the eruption. The quartzose sandstone above the ignimbrite is ~70 m thick and occurs at a stratigraphic height of ~690 m above the base of the ignimbrite where the sandstone appears to interfinger with the top of the ignimbrite unit (Fig. 4). Sedimentary structures in the quartzose sandstone are poorly preserved, showing only local planar lamination, and therefore the depositional environment is uncertain. The rhyolite ignimbrite (Jsl1) and overlying volcanic units show no evidence for interaction with water and thus have been interpreted as subaerial deposits (Schermer and Busby, 1994), although the quartzose sandstones may have formed during fluvial or lacustrine reworking associated with pauses in volcanic activity. The compositional similarity of the rhyolite ignimbrite throughout its thickness (see Schermer and Busby, 1994) suggests that the thin sandstone within the ignimbrite represents less time than typical intereruptive intervals for small rhyolite calderas ($\sim 10^2 - 10^5$ yr; e.g., Cas and Wright, 1987); absolute-age constraints discussed subsequently suggest that the upper sandstone unit could represent anywhere from ~2 m.y. to 28 m.y.

Sidewinder Mountain and adjacent regions. The Fairview Valley Formation–Sidewinder volcanic series contact is sharp and planar along its ~400 m of exposure at Tricolor Quarry on the eastern flank of Sidewinder Mountain (Figs. 3, 4). The Fairview Valley Formation here consists of dolomite-cobble conglomerate intercalated with and overlain by lesser amounts of thin-bedded siltstone, quartzose sandstone, and calcareous siltstone (Miller, 1981). Although the conglomerate facies at Tricolor Quarry is similar to that at Black Mountain, no distinct quartzose sandstone is present above the conglomerate, and Miller (1981) interpreted the overlying volcanic rocks to be in fault contact. However, bedding in the Fairview Valley Formation and pumice compaction foliation in the overlying rhyolite ignimbrite (unit Jsl1) are parallel to each other and to the contact. The basal ~1 m of the rhyolite ignimbrite contains fine-grained lithic fragments of calcareous siltstone. We suggest that the concordant and unsheared appearance of the contact, together with the presence of clasts probably derived from the underlying Fairview Valley Formation, indicates that the contact is depositional.

Miller (1981) noted that the composition (carbonate-cobble conglomerate intercalated with fine-grained rocks) of the Fairview Valley Formation at Tricolor Quarry strongly resembles the upper parts of the Black Mountain section, but expressed uncertainty about its stratigraphic position. However, our reinterpretation of the Black Mountain quartzite as gradational upward from the carbonate-cobble conglomerate wedge would allow for such lateral facies variation. We infer that quartzose sandstones are more abundant in the finer-grained subaqueous basinal facies and fringing fan-delta facies at Black Mountain than would be expected in the subaerial or more proximal fan-delta facies at Tricolor Quarry.

The Fairview Valley Formation also crops out at two locations southwest of Sidewinder Mountain on the eastern margin of Fairview Valley (Fig. 1). In the more northern locality, calcareous siltstones of the Fairview Valley Formation occur as a megabreccia block within caldera-margin facies of one of the major ignimbrite units (Jsl2) of the Sidewinder volcanic series (Schermer and Busby, 1994). In the more southern locality, Fairview Valley Formation occurs in fault contact against another ignimbrite unit (Jsl4). The limited exposure of Fairview Valley Formation in these areas prevents further consideration of the facies or paleogeographic significance.

Source terranes and depositional environment of the Fairview Valley Formation

The provenance of the coarse-grained upper part of the Fairview Valley Formation and the transitional sequence includes three distinct sources: metamorphic basement rocks, arc-type volcanic rocks, and a quartz-rich terrane. Nearby Precambrian to Paleozoic basement was an important source for conglomerate clasts including calcitic and dolomitic marble, quartzite, chert, foliated granite, and gneiss (Miller, 1978b, 1981). Laterally restricted carbonate-cobble conglomerates were derived from Paleozoic limestone and dolomite as young as Early Permian (Bowen, 1954; Miller, 1978b, 1981). Intermediate-composition to silicic volcanic clasts also occur in the conglomerates, and interlayered sandstones contain both texturally mature quartz sand grains and angular (volcanic?) crystals; the matrix composition cannot be positively identified owing to alteration but appears to contain quartz and altered volcanic debris.

Volcanic detritus is abundant only near the contact between the Fairview Valley Formation and the Sidewinder volcanic series; Miller (1978a, 1978b, 1981) reported only "minor" silicic volcanic clasts at lower stratigraphic levels. The intermediate-composition volcanic clasts in the volcaniclastic conglomerates (svs) of the transitional sequence at Quartzite Mountain closely resemble the immediately adjacent andesite lavas and shallow intrusions (Jsla, Fig. 2B, column 1). Further, upper levels of the volcaniclastic unit (svs) at Quartzite Mountain are definitely interlayered with dacitic to andesitic lithic lapilli tuff and may be interlayered with andesite lavas and rhyolite ignimbrite (Fig. 2B, column 3). The angularity and abundance of the clasts and the presence of the tuffs suggest a nearby active volcanic source, and the similarity in textures and compositions to those of the lower part of the Sidewinder volcanic series suggests that these rocks or their precursors were the source of volcanic detritus in the Fairview Valley Formation. However, there are no primary volcanic rocks at the lowest stratigraphic levels of the transitional sequence, and intermediate-composition volcanic rocks of Permian age are also a possible source for the volcanic debris. Permian basaltic and andesitic volcanic rocks occur in the El Paso Mountains (Carr et al., 1984), and minor low-grade metabasaltic or andesitic rocks of inferred Permian age occur in the Goldstone–Lane Mountain area (Miller and Sutter, 1982). Metamorphic rocks (talc-chlorite schist) of uncertain protolith and age in the Shadow Mountains were inferred to be derived from Permian volcanic rocks (Martin and Walker, 1995). Although it is possible that these rocks could have formed a source terrane for the Fairview Valley Formation and the transitional sequence, we consider it unlikely because of the sparse occurrence of inferred Permian volcanic rocks south of the Garlock fault, the absence of silicic volcanic rocks in the Permian sequences, and the close similarity of the clasts to adjacent exposures of the Sidewinder volcanic series.

Sandstone and siltstone in most of the Fairview Valley Formation are arkosic (Miller, 1978a, 1981) whereas those in the upper 90–150 m of the stratigraphic section at Quartzite Mountain and Black Mountain (including Miller's quartzite unit) are more quartz rich and contain up to 90% well-rounded quartz grains. The source of the mature quartz sand may have been any one of several ergs (sand seas) that were active in the Colorado Plateau region in Early and Middle Jurassic time (discussed later in this paper), but there is no direct evidence for an eolian depositional environment. The stratigraphy of the Fairview Valley Formation, notably the increasing volcanic and quartz components upward in its section, suggests that the provenance changed over the course of its deposition, from basement sources to arc-type volcanic and cratonal eolian sources.

Our new data support the interpretation of Miller (1978a, 1978b, 1981) that the Fairview Valley Formation was primarily deposited in a shallow-marine or lacustrine environment and in local alluvial-fan (fan-delta) subenvironments. Regional correlation favors the shallow-marine interpretation (see later discussion). We reinterpret the upper part of the formation to grade, over several tens to a few hundred meters of section, into quartz-rich sandstones, volcanic lithic breccias and sandstones, and ignimbrites typical of the Jurassic arc. Thus it appears that volcanism in this part of the arc overlapped in time with marine sedimentation. However, only volcanic lithic sandstones and breccias—i.e., no primary volcanic rocks other than possible thin tuffs—are observed interlayered with the shallow-marine rocks, and the bulk of the Sidewinder volcanic series was deposited subaerially (Schermer and Busby, 1994). Thus it appears that the stratigraphy near the contact records a transition from shallow-marine and lacustrine to subaerial environments at the same time that the arc became established.

Facies differences between the various fault blocks of Fairview Valley Formation appear to record a transition from shallower facies in the east (Tricolor Quarry) to deeper facies in the west (Black Mountain and Quartzite Mountain) that was maintained until shortly after the initiation of volcanism (Fig. 4). At Tricolor Quarry, the volcanic sequence overlies carbonate-clast conglomerate of the fan-delta facies of the Fairview Valley Formation. At Black Mountain we see the transition from fan-delta conglomerates to shallow-marine(?) siltstone and sandstone over a lateral distance of ~600 m westward (Miller, 1978a, 1981); the earliest ignimbrite overlaps this facies transition and contains interlayered quartzose sandstones similar to those in the underlying Fairview Valley Formation, but does not contain evidence of submarine deposition. At Quartzite Mountain, the transition from the Fairview Valley Formation to the Sidewinder volcanic series is interpreted to record subaqueous gravity flows of volcanic debris intercalated with fine-grained well-laminated calcareous siltstones that may be shallow marine, but the primary volcanic rocks of the Sidewinder volcanic series appear to be subaerial (Schermer and Busby, 1994). Volcanic, volcaniclastic, and minor quartzose strata above the oldest ignimbrite (Jsl1) are also thicker at Quartzite Mountain (up to 200 m) than at Black Mountain (~130 m) and Sidewinder Mountain (0 m) and overlap the edge of the caldera formed during eruption of Jsl1, thus suggesting that the westward-deepening basin persisted through the local onset of volcanism.

The lack of a significant time gap between Fairview Valley shallow-marine deposition and the initiation of arc volcanism is suggested by the presence of the volcaniclastic unit (svs) of the transitional sequence at Quartzite Mountain (Fig. 2B, columns 1, 3). The age range of the transitional sequence is unknown, and the change from Fairview Valley Formation deposition to arc volcanism could represent significant time. However, if our interpretation of the depositional environment is correct, rapid sedimentation of sediment-rich gravity flows could have produced the maximum ~300-m-thick sequence in <0.3–3 m.y., on the basis of typical sedimentation rates of 100–1000 m/m.y. in active basins (e.g., foreland and rift basins; Leeder, 1999).

Age of the Fairview Valley Formation

The age of the Fairview Valley Formation has important implications for the timing of deformation and changes in paleogeography in the Mojave Desert region. The Fairview Valley Formation unconformably overlies monzonite at Black Mountain that intrudes deformed Precambrian and Paleozoic sequences (Fig. 4; Miller 1978b, 1981), and thus the age of the Fairview Valley Formation places an upper limit on the deformation and plutonism interpreted to be associated with continental-margin truncation and the initiation of the magmatic arc (Walker, 1988). Walker (1987) considered the formation to be Early Triassic in age from the presence of conodonts as young as Early Triassic and by correlation with better-dated sequences to the east. More recent U-Pb data from the Black Mountain monzonite is interpreted to reflect crystallization at 243 ± 2 Ma (Miller et al., 1995); however, we reinterpret the age as ca. 236 Ma (see subsequent discussion). These data—together with recent revisions to the geologic time scale that place the Permian–Triassic boundary at 251 ± 0.3 Ma (Bowring et al., 1998) and the boundary between the Anisian and Ladinian Stages of the Middle Triassic at either 240.7 or 241.3 Ma (Mundil et al., 1996)—indicate that the base of the Fairview Valley Formation is late Anisian or younger. The age of the boundary between the Lower Triassic and the Middle Triassic is, however, poorly determined (Gradstein et al., 1994).

The age of the Black Mountain monzonite is of considerable importance to this study, because the age of the base of the Fairview Valley Formation is not tightly defined. We reevaluate the Miller et al. (1995) data to interpret the age as ca. 236 Ma. Miller et al. (1995) analyzed five fractions of zircon from the monzonite. Two multigrain fractions are concordant within errors, one with a $^{206}Pb^{*}/^{238}U$ age of 236.0 ± 1.2 Ma (where the * indicates radiogenic) and a $^{207}Pb^{*}/^{206}Pb^{*}$ age of 236.7 ± 3 Ma, and the other with a $^{206}Pb^{*}/^{238}U$ age of 236.1 ± 1.3 Ma and a $^{207}Pb^*/^{206}Pb^*$ age of 239.1 ± 3 Ma. An air-abraded, single, large (>60 mesh) zircon was discordant with a $^{206}Pb^*/^{238}U$ age of 235.8 ± 1.3 and an older $^{207}Pb^*/^{206}Pb^*$ age of 243.4 ± 2 Ma. The other fractions are also discordant, one with a Pb/Pb age of 260 Ma. Miller et al. (1995, p. 1449) interpreted the Pb/Pb age of the single grain "as the most likely crystallization age." We find this interpretation is not supported by isotopic systematics of this sample and prefer the alternative interpretation that the two concordant fractions at ca. 236 Ma yield the most likely crystallization age of the monzonite. The slightly older Pb/Pb age of the large single grain reflects minor inheritance. With this interpretation, the base of the Fairview Valley Formation is probably Ladinian or younger.

On the basis of (1) the evidence for gradational contact between the Fairview Valley Formation and the Sidewinder volcanic series and (2) new U-Pb data presented subsequently, we conclude that at least part of the Fairview Valley Formation is late Early Jurassic in age. The basal Sidewinder ignimbrite (Jsl1, Fig. 3) at Black Mountain and Sidewinder Mountain yields similar U-Pb ages of 171 ± 9 (Graubard et al., 1988) and 179.5 ± 3.0 (this study; see subsequent section), respectively. This unit is correlated with the lowest ignimbrite at Quartzite Mountain (Fig. 4; Schermer and Busby, 1994). These data suggest that at least the upper calcareous siltstones, the cobble conglomerates, and the quartz-rich and volcanogenic sandstone-siltstone parts of the sequence are late Early or early Middle Jurassic. The apparent absence of any major breaks within the Fairview Valley Formation suggests that the entire formation may be Jurassic.

AGE OF THE SIDEWINDER VOLCANIC SERIES

Further constraints on the early evolution of the magmatic arc and its relationship to quartzose sand deposition in the central Mojave block are provided by examining the time span recorded by the Sidewinder volcanic series. Stratigraphic, volcanologic, and compositional details of the Sidewinder volcanic rocks are given in Schermer and Busby (1994) and are not repeated here, but are summarized in Figure 3A. We report here new U-Pb ages for the predominant volcanic units.

Samples ~90 kg each of the four major ignimbrite units (Jsl1–Jsl4) of the lower Sidewinder volcanic series were collected at Sidewinder Mountain. Although all ignimbrites except Jsl1 contain flow units with lithic lapilli (Fig. 3), we sampled outcrops and flow units with no visible lithic fragments. A sample of a rhyolite dike from the Upper Sidewinder volcanic series was collected near where it crosscuts a normal fault between an ignimbrite unit (Jsl3) and the Fairview Valley Formation (Fig 3). Zircons were separated from the samples by the usual methods of crushing, Wilfley table concentration, heavy-liquid and magnetic separation, and handpicking.

U-Pb zircon dating of ignimbrites presents various challenges. First, the petrogenesis of these high-silica rocks commonly involves incorporation of some preexisting crustal components, leading to some zircon inheritance. In the simplest case, the inherited zircons are of a single age, but in more complicated cases, their ages fall in a range. Next, eruption of the ignimbrite and its energetic flow over the Earth's surface can lead to entrainment of mineral grains, including zircons, from unconsolidated sediments at the ground surface. Finally, as in all zircon dating, there is the likelihood of some postdepositional Pb loss via a range of mechanisms.

In order to minimize age uncertainties related to the factors previously discussed, we first carefully handpicked all zircon grains that showed any rounding, pitting, or frosting inferred to reflect surficial (eolian?) processes. These "entrained" zircon fractions were analyzed separately. The more euhedral, unfrosted zircons were split into a series of fractions by size, shape, etc., and regarded as "igneous" zircons. By this term, we include not only newly crystallized zircon, but also any inherited components from the source(s) of the magma. Obviously, it is difficult to totally exclude every entrained zircon as some with minimal exposure to surficial processes closely resemble the igneous zircons. This is an important point because the age or age range of the entrained zircons is not necessarily representative of the age or age range of the inherited components in the igneous zircon population.

We attempted to minimize the effects of any posteruptive Pb loss by applying step-wise dissolution techniques to the zircon analyses (e.g., Busby-Spera et al., 1990; Mattinson, 1994). Each fraction of zircon reported is actually the residue left after partial digestion of the zircons at either 80°C for 16 days or 160°C for 24 h in 50% HF plus a small amount of nitric acid. In some cases, the partial digestion represents a single step; in others, a preliminary, lower-temperature step preceded the 160°C step. A full discussion of the partial-digestion steps is beyond the scope of this paper. However, in all cases, the measured ages of the residues are older than ages of the "bulk" zircon fractions obtained by recombining the results from the residues plus the partial dissolution step(s). This result indicates that the bulk fractions had in fact lost some Pb, but suggests that much or all of the disturbed zircon material was removed by the partial dissolution step(s). After these grain-selection and analysis methods, some of the samples show reasonably well defined arrays on concordia diagrams that we interpret to yield lower intercepts indicating the age of eruption and upper intercepts reflecting the age (or a limited range in ages) of the inherited components. Other samples still show considerable scatter about the regression lines. This scatter probably results from a range in ages of inherited components (including any entrained zircons we failed to recognize and remove) and/or from our inability to remove all the effects of later Pb loss by our partial-dissolution approach.

The results for the zircon-residue analyses are presented in Table 2 and Figure 5. The oldest unit, a crystal-poor welded rhyolite ignimbrite collected at Tricolor Quarry (Fig. 3; Jsl1, sample AV113, yields a reasonably well-defined lower-intercept age of 179.4 ± 3.4 Ma, and a poorly defined upper-intercept

TABLE 2. U-Pb DATA FOR SIDEWINDER VOLCANIC SERIES

Sample	Mass (mg)	Concentration (ppm)		Isotopic ratios†				
		^{206}Pb*	^{238}U	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{204}Pb/^{206}Pb$	$^{238}U/^{206}Pb$*	^{207}Pb*/^{206}Pb*
89AV111-1	0.5	4.643	167.1	0.2191 (2)	0.06246 (3)	0.000117	31.143 (203.8 ± 2.0)	0.06078 (631 ± 6)
89AV111-3	1.9	3.221	139.5	0.2572 (2)	0.05214 (2)	0.000046	37.481 (169.7 ± 1.7)	0.05147 (262 ± 2)
89AV111-5	4.1	3.023	133.2	0.2621 (2)	0.05187 (2)	0.000039	38.139 (166.8 ± 1.7)	0.05130 (254 ± 2)
89AV111-6	2.3	1.941	83.65	0.2589 (2)	0.05327 (2)	0.000145	37.327 (170.5 ± 1.7)	0.05115 (248 ± 3)
89AV112-1	5.7	5.577	237.9	0.2262 (2)	0.05218 (2)	0.000113	36.914 (219.0 ± 2.2)	0.05053 (219 ± 2)
89AV112-2	0.3	4.555	178.8	0.2294 (2)	0.05790 (2)	0.000217	33.967 (187.1 ± 1.9)	0.05474 (402 ± 2)
89AV112-3A	6.9	5.019	221.6	0.2178 (2)	0.05124 (2)	0.000015	38.212 (166.5 ± 1.7)	0.05101 (241 ± 2)
89AV112-3B	4.5	5.104	215	0.2150 (2)	0.05192 (2)	0.000039	36.469 (174.4 ± 1.7)	0.05134 (256 ± 2)
89AV112-5A	3.8	4.576	197.2	0.2145 (2)	0.05178 (2)	0.000058	37.299 (170.6 ± 1.7)	0.05093 (238 ± 2)
89AV112-5B	2.5	3.506	146.4	0.2170 (2)	0.05362 (2)	0.000171	36.153 (175.9 ± 1.8)	0.05112 (246 ± 2)
89AV113-1	4.2	3.322	120.57	0.3683 (3)	0.05777 (2)	0.000105	31.407 (202.0 ± 2.0)	0.05625 (462 ± 3)
89AV113-2A	0.2	3.445	125.7	0.3700 (3)	0.05826 (2)	0.000085	31.576 (201.0 ± 2.0)	0.05702 (492 ± 2)
89AV113-2	4.7	9.514	390.1	0.4135 (3)	0.05435 (2)	0.000301	35.486 (179.1 ± 1.8)	0.04994 (192 ± 4)
89AV113-4	2.1	7.557	296.2	0.4051 (3)	0.05405 (2)	0.000160	33.921 (187.3 ± 1.9)	0.05170 (272 ± 2)
89AV113-5	1.9	6.654	266.6	0.4134 (3)	0.05358 (2)	0.000198	34.698 (183.2 ± 1.8)	0.05069 (227 ± 2)
89AV113-6	0.2	6.231	243.7	0.5058 (4)	0.09516 (9)	0.002990	34.554 (183.9 ± 1.8)	0.05144 (260 ± 30)
89AV114-1	0.1	5.61	271.1	0.4698 (3)	0.05116 (2)	0.000122	41.916 (152.0 ± 1.5)	0.04938 (166 ± 10)
89AV114-2	0.1	5.912	286	0.4716 (3)	0.04962 (2)	0.000101	41.941 (151.9 ± 1.5)	0.04962 (177 ± 4)
89AV114-3	0.2	5.594	265.7	0.4364 (3)	0.05081 (2)	0.000040	41.142 (154.8 ± 1.5)	0.05023 (206 ± 3)
89AV114-4	0.1	5.773	252.6	0.3966 (2)	0.05721 (5)	0.000171	37.985 (167.5 ± 1.7)	0.05472 (401 ± 19)
89AV13-1	2.8	2.499	91.65	0.2648 (2)	0.06848 (2)	0.000179	31.746 (200.0 ± 2.0)	0.06591 (804 ± 3)
89AV13-3A	4.1	2.523	112.6	0.3062 (2)	0.05624 (2)	0.000126	38.625 (164.8 ± 1.6)	0.05440 (388 ± 2)
89AV13-3B	1.5	2.535	115.6	0.3142 (2)	0.05470 (2)	0.000115	39.463 (161.3 ± 1.6)	0.05302 (330 ± 4)
89AV13-4	0.9	1.629	78.31	0.3535 (2)	0.05266 (4)	0.000211	41.615 (153.1 ± 1.5)	0.04957 (175 ± 8)
89AV13-5	4.9	3.791	164	0.2980 (1)	0.05469 (2)	0.000035	37.467 (169.8 ± 1.7)	0.05418 (378 ± 2)
89AV13-8	2.4	5.293	234.3	0.3139 (1)	0.05416 (2)	0.000054	38.358 (165.9 ± 1.7)	0.05338 (345 ± 2)

*Radiogenic.

†$^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{204}Pb/^{206}Pb$ ratios = measured ratios, corrected for 0.125%/amu isotopic fractionation and for isotopic composition of spike. Errors on most $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios are controlled by ±0.03%/amu uncertainty in the fractionation correction. Errors for the $^{204}Pb/^{206}Pb$ ratios are typically in the 1% range. Calculated isotopic ratios for Tera-Wasserburg concordia diagram shown with calculated ages and uncertainties on the least significant digit(s) shown in parentheses. We have assigned a conservative 1% error to the $^{238}U/^{206}Pb$* ratios to account for any minor fractionations during the step-wise dissolution procedure.

For other analytical details, see Mattinson (1994).

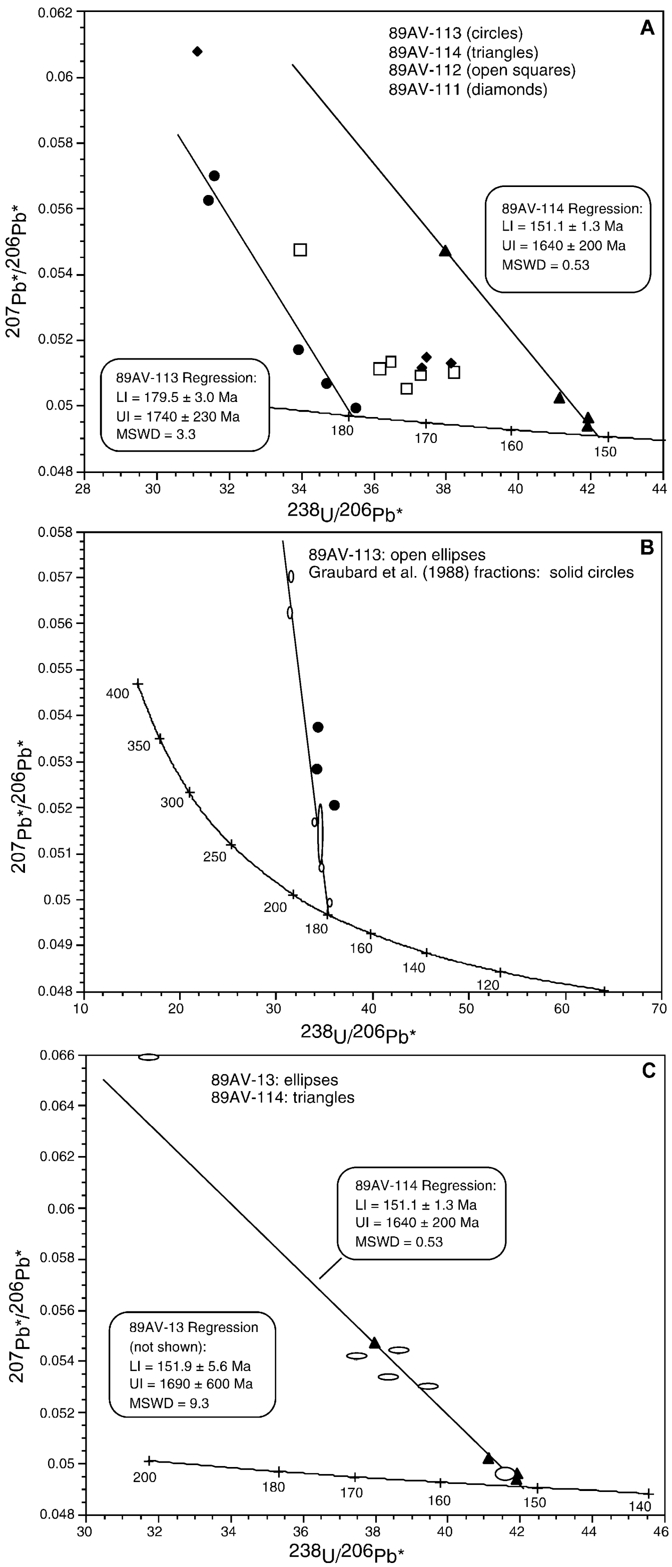

Figure 5. Tera-Wasserburg concordia plots for Sidewinder volcanic series. (A) Data for ignimbrites from the lower part of the Sidewinder volcanic series. Regressions shown for 89AV-113 (Ludwig, 1991, model 4 lower-intercept fit) and 89AV-114 (Ludwig, 1991, model 1 fit). LI—lower-intercept age, UI—upper-intercept age, MSWD—mean square of weighted deviates. (B) Data from Graubard et al. (1988), with the data and regression line for the oldest ignimbrite, 89AV-113, shown for reference. See text for discussion. Only the three igneous fractions from Graubard et al. (1988) are shown. The fourth Graubard fraction is a handpicked fraction of rounded, frosted, entrained zircons and is not necessarily representative of the inherited components in the "igneous fraction." For this reason we have not included it here. (C) Data for 89AV-13 and 89AV-114. The data and regression line for the youngest lower Sidewinder volcanic series ignimbrite (89AV-114) are shown for comparison with the more scattered 89AV-13 data. See text for further discussion.

age of 1680 ± 440 Ma, on the basis of six fractions of zircon (Fig. 5A). The ages are based on a lower-intercept fit according to model 4 of Ludwig (1991). The MSWD (mean square of weighted deviates) of 3.3 indicates moderate real scatter in the data. We interpret the lower-intercept age of 179.4 ± 3.4 as the eruption age of AV113 and as the best estimate of the age of the base of the section. Because this result is based on large, multigrain fractions rather than single-grain analyses, a reviewer has suggested that we should use our lower-intercept ages, or perhaps even the $^{207}Pb/^{206}Pb$ age of the fraction with the least inheritance, as maximum ages. Certainly the lowest Pb/Pb age of 192 ± 4 for fraction 89AV113-2 is an absolute maximum age for the sample, but this age clearly reflects a significant inherited component. The lower intercept might more properly be regarded as a *minimum* age because of the possibility of minor posteruptive Pb-loss effects that we might not have totally removed with our partial-dissolution methods. However, the overall result from six fractions indicates a rather well-behaved system, and we prefer our interpretation that 179.4 ± 3.4 Ma is the best measure of the eruptive age of the sample.

Graubard et al. (1988) reported a lower-intercept age of 171 ± 9 Ma on a sample collected from Black Mountain that we think is correlative with our sample AV113 on the basis of lithology and petrology. This age overlaps within its rather large errors with our lower-intercept age of 179.4 ± 3.4 Ma. The Graubard et al. (1988) age was based on three igneous fractions, plus one strongly rounded, frosted entrained fraction. The igneous fractions show considerable scatter and do not, by themselves, define a discordia line with reasonable errors. The reported age was obtained by using the entrained fraction to pin the upper end of the discordia line. Moreover, only one of the Graubard et al. (1988) fractions was subjected to a light "leach" procedure. The three igneous fractions are plotted in Figure 5B along with the AV113 data and the regression line for reference. The entrained fraction would plot well off scale and is not shown. The Graubard igneous fractions all plot slightly to the right of the AV113 regression line. The slightly leached fraction (the middle one) lies closest to the regression line. This result suggests that all of the Graubard fractions reflect slight Pb loss. We interpret these results as indicating that the two units are in fact correlative at ca. 179 Ma.

Stratigraphically above AV113 are two samples of dacitic ignimbrites. Sample AV112 was collected from near the top of a $>$1400-m-thick ignimbrite (Jsl2) that is zoned from rhyolite to dacite. The contact of this unit with Jsl1 is not well exposed anywhere in the region, and Schermer and Busby (1994) and Schermer (1993) interpreted the contact to be conformable. Reanalysis of our map data, however, suggests the possibility of up to 10°–15° of angular discordance. Sample AV111 was collected from a dacitic tuff breccia unit (Jsl3) that depositionally overlies Jsl2 (Schermer and Busby, 1994). The two units represent nearly half of the $>$4 km thickness of the lower part of the Sidewinder volcanic series. Schermer and Busby (1994) reported that a period of depositional reworking occurred following eruption of Jsl2, but bedding and pumice-compaction foliations above and below the top of Jsl2 are parallel. There was also a probable period of erosion following emplacement of unit Jsl3, as evidenced by the absence of sedimentary rocks and unit Jsl3 beneath several of the sections of the overlying ignimbrite (Jsl4). Although the original depositional contact above unit Jsl3 is poorly exposed or affected by intrusion or faulting, the fact that the pumice compaction foliation appears subparallel in units above and below the contact (maximum of ~5°–10° discordance) suggests minimal tectonic activity at that time.

The U-Pb data yield lower-intercept ages for AV-112 and AV-111 of 164 ± 10 Ma (six fractions, MSWD = 13) and 163.1 ± 6.5 Ma (four fractions, MSWD = 5), respectively. As can be seen in Figure 5, and also from the large MSWD values, the zircon fractions show considerable scatter, and we have not shown the regression lines in Figure 5. Nevertheless, the zircon data are consistent with the stratigraphic position of these units between the more precisely dated AV113 unit below them and the AV114 unit above them (discussed subsequently). Despite the large error on the sample from unit Jsl2, map relationships demonstrate it is no younger than Jsl3. Unit Jsl2 closely resembles deformed dacitic meta-volcanic rocks of the Hodge Volcanics at Iron Mountain to the north (Fig. 1), dated at 164 ± 2 (minimum, lower-intercept age) by Boettcher and Walker (1993). Our age data are consistent with the suggestion of Boettcher and Walker (1993) that the units are correlative.

The youngest ignimbrite (Jsl4, AV114), a dacite lithic lapilli ignimbrite, is also the thickest ($>$1.7 km) and the most complex, with several eruptive units separated by intervals of reworking (Schermer and Busby, 1994). The sample was collected from a pumice-rich, lithic-poor layer at Sidewinder Mountain from the upper half of unit Jsl4 but, because the base is intruded and the top is faulted, the exact stratigraphic level is uncertain. The sample is stratigraphically above at least two intervals of reworked tuff. The lower-intercept age of this sample is 151.0 ± 1.3 Ma (Fig. 5), based on four fractions of igneous zircon, and is interpreted as the eruption age of the sample.

The only sample of the Upper Sidewinder volcanic series (AV13) was obtained at Black Mountain from a rhyolite dike that crosscuts a normal fault between an ignimbrite (unit Jsl3) in the Lower Sidewinder volcanic series and the Fairview Valley Formation (Fig. 3). The northwest-trending rhyolite and basaltic dikes at Black Mountain and elsewhere in the region are correlated with the Independence dike swarm (Karish et al., 1987) and are interpreted to be the feeders for rhyolite and basalt lavas that overlie tilted ignimbrites along an angular unconformity (Schermer and Busby, 1994). Six fractions of igneous zircons from the dike sample yield a lower-intercept age of 151.9 ± 5.6 Ma that is within error of sample AV-114 (Fig. 5). The relatively large error in the lower-intercept age for AV13 results from considerable scatter in the data. The intercept age itself is strongly dependent on the one fraction that is almost concordant. Although at the sampling locality we cannot determine crosscutting relationships between the dike and the youngest ignimbrite (AV-114), relationships at Ritz Mountain to the north and at Stoddard Ridge to the northeast (Fig. 3) indicate that (1) quartz monzonite intrudes unit Jsl4 and (2) the northwest-trending dike swarm intrudes both the quartz monzonite and unit Jsl4 and thus must be younger. The age is consistent with other ages of ca. 150 ± 2 Ma determined from the Independence dike swarm in the eastern Sierra Nevada and the greater Mojave Desert region (Carl et al., 1998; Chen and Moore, 1979; James, 1989; Lahren et al., 1990).

The apparent gap in time from ca. 179 to ca. 164 Ma between the two oldest ignimbrite units (Jsl1, Jsl2) suggests the possibility of an unconformity; because of the large error on sample AV112, however, the time gap could be as short as 2 m.y. or as long as 28 m.y. Three pieces of evidence—the slight angular discordance; the existence of local deposits of fluvially reworked tuff, andesite lava, and minor quartzose sandstones up to 200 m thick between the two ignimbrite units at Black Mountain and Quartzite Mountain; and the absence of such deposits at Sidewinder Mountain (Schermer and Busby, 1994)—suggests some deposition, erosion, and perhaps some faulting, between the two caldera-forming eruptions. Quartzose sandstones identical to those in the upper Fairview Valley Formation occur at the top of the lower ignimbrite (Jsl1), but volcaniclastic sandstones farther up section contain only minor rounded quartz grains, thus suggesting a waning of the source of mature quartz sand. Thus the best estimate of age of the quartzose sandstones is ca. 180 Ma.

Our new age data provide important age constraints on a period of north-south extension in the Mojave Desert. The time span between the ca. 163 and ca. 151 Ma eruptions (which produced units Jsl3 and Jsl4, Fig. 3) is marked by a period of differential erosion, deposition, and possible minor faulting. However, the major angular unconformity in the Victorville region (~45°–60°) occurs above the upper ignimbrite (Jsl4), be-

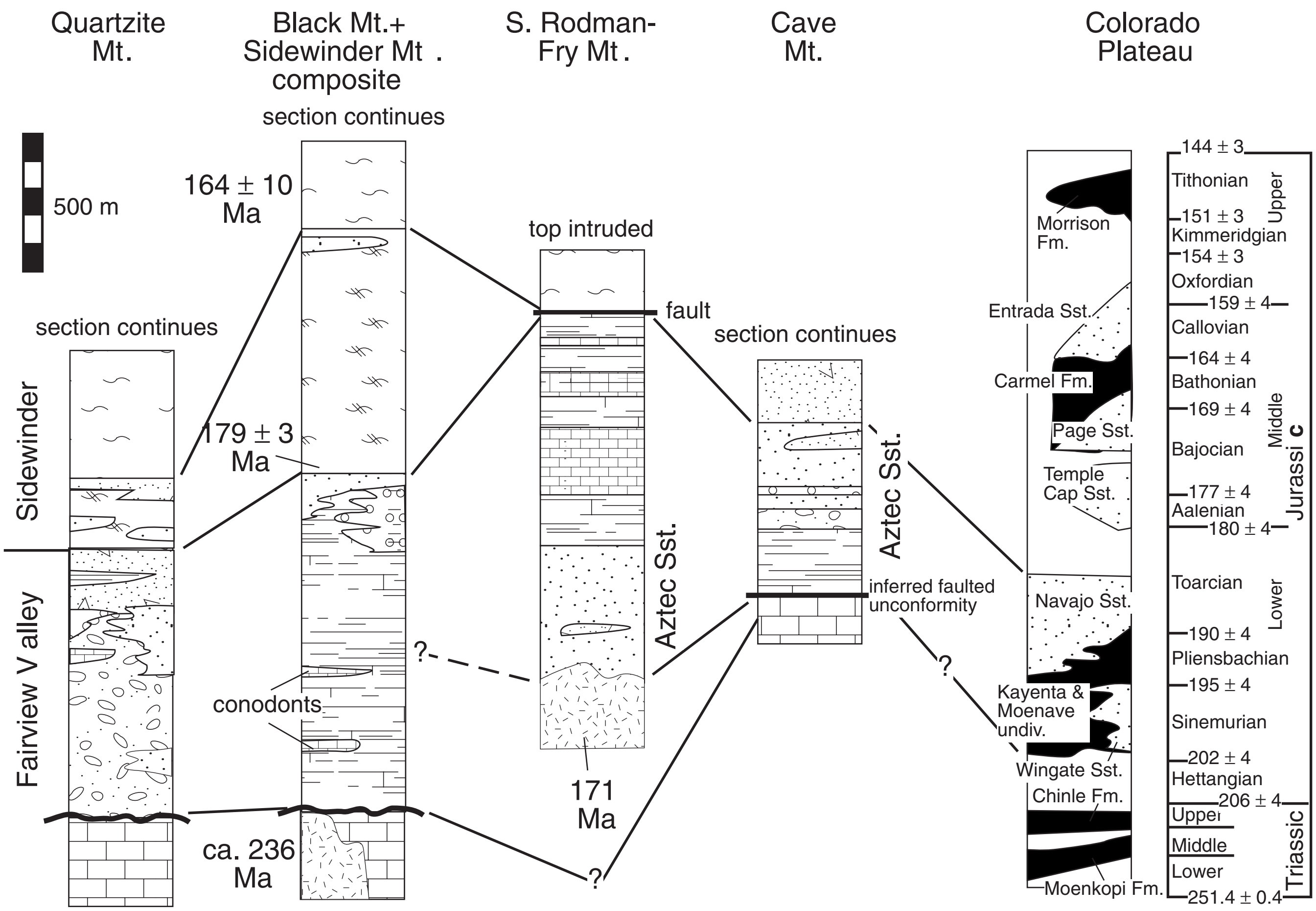

Figure 6. Correlation of lower Mesozoic sequences from the central Mojave block and Colorado Plateau, with new U-Pb dates shown in bold. Stratigraphy modified from the following: Quartzite Mountain and Sidewinder Mountain—Miller (1978a, 1978b, 1981) and Walker (1987); Rodman Mountains—Miller (1978a, 1978b, 1981), Miller and Carr (1978), and Karish et al. (1987); Cave Mountain—Miller and Carr (1978), Cameron et al. (1979), and Miller and Cameron (1982); Colorado Plateau—Blakey et al. (1988) and Peterson (1994). See Figure 1 for locations.

tween the Lower and Upper Sidewinder volcanic series. The unconformity is interpreted to be due to extension, tilting, and intrusion of quartz monzonite plutons (Schermer 1993; Schermer and Busby, 1994). Structures documented by Schermer (1993) include several large-displacement normal faults that together accomplished ~15% extension between the time of emplacement of the Lower and Upper Sidewinder volcanic series. Both Upper and Lower Sidewinder volcanic series were then folded about northwest-trending axes. The concordia intercept ages and age uncertainties (at their extremes) of the Upper Sidewinder dike (AV13) and the Lower Sidewinder ignimbrite (AV114; Fig. 6) permit a *maximum* of 6 m.y. to have elapsed between ignimbrite eruption, reworking, intrusion by quartz monzonite, tilting, uplift, erosion, and intrusion and overlap by Independence dikes and equivalent lavas. The quartz monzonite beneath the unconformity is only dated in the Fry and Ord Mountains to the east (Fig. 1B), at 166–171 Ma (Ar/Ar hornblende; Karish et al., 1987), where a similar sequence of events is recognized, but where the ignimbrites have not been dated. Northeast-southwest shortening, possibly associated with dextral transpression (Schermer, 1993) must have occurred after 151 Ma and prior to the emplacement of the undeformed Late Cretaceous (ca. 75 Ma; Miller and Morton, 1980) plutonic suite.

CORRELATIONS WITH OTHER PARTS OF THE ARC

Facies characteristics of the Upper Jurassic rocks in the central Mojave block suggest that this region occupied a location transitional between marine (outboard and to the north) and nonmarine (inboard and to the south) parts of the arc in Early Jurassic time. In this section we briefly describe some of the other Mojave sequences and propose new correlations between the eastern and western Mojave that suggest that a marine transgression occurred in the Mojave block during Early Jurassic time.

Southern Rodman Mountains

We correlate the Fairview Valley Formation in the Victorville region with Mesozoic volcanic and sedimentary rocks in the Rodman and Fry Mountains (Fig. 1) studied by Miller and Carr (1978) and Karish et al. (1987). In that area, eolian quartz arenite is overlain by calcareous siltstone, quartz arenite, limestone, and volcanic-cobble conglomerate interpreted to have been deposited in a lacustrine or shallow-marine environment during volcanic arc activity (Fig. 6; Miller and Carr, 1978). Rhyolite ignimbrite that occurs in fault contact with the quartz arenite is correlated with unit Jsl2 in the Victorville region (Fig. 3A; Schermer and Busby, 1994). Although no depositional contact is exposed in the Rodman Mountains, the ignimbrite contains clasts of calc-silicate and quartz arenite that may have been derived from the shallow-marine sequence, although older sources for the clasts are possible. We infer a relationship similar to that observed farther to the west at Quartzite Mountain and Black Mountain, with ignimbrite eruption following shallow-marine deposition; however, unit Jsl1 is not present in the Rodman Mountains. In agreement with Miller and Cameron (1982), we correlate the eolian quartz arenite in the Rodman Mountains with quartzose sandstone at Black Mountain (the quartzite unit of Miller, 1981); we further correlate the associated calcareous rocks with the upper part of the Fairview Valley Formation on the basis of similar lithology (in particular, interlayered volcanic-clast conglomerates), facies (shallow marine), and age relative to the Sidewinder ignimbrites (units Jsl1 and Jsl2).

Our correlation of the Rodman Mountains strata with the Fairview Valley Formation and Sidewinder Volcanic Series suggests an Early Jurassic age for the eolian quartz arenite, in agreement with Miller and Carr's (1978) correlation of the eolianites with the Aztec Sandstone in the Spring Mountains of Nevada. Both upper and lower contacts are faulted or intruded, and there are no fossils in the sequence. However, age constraints are provided by the younger (164 $\pm$ 10 Ma, Jsl2) ignimbrite and by crosscutting plutonic rocks ~5 km to the southwest dated at 170.8 $\pm$ 0.4 Ma (two Ar/Ar plateau ages on hornblende; Karish et al., 1987). Although these data could be interpreted to indicate an Early or Middle Jurassic age for the eolianites, correlation with strata on the Colorado Plateau (discussed subsequently) suggest that an Early Jurassic age is more likely.

Eastern Mojave Block

Calcareous rocks intercalated with quartz arenites and volcanic and volcaniclastic rocks in the Victorville region and areas as far east as Cave Mountain (Figs. 1, 6) provide evidence that shallow-marine conditions in the Mojave segment of the magmatic arc persisted into Middle Jurassic time in a fairly wide area. At Cave Mountain (Fig. 6), Cameron et al. (1979), Miller and Cameron (1982), and Walker (1987) described a sequence of marble, calc-silicate hornfels, metaconglomerate, and quartzite that is interpreted to overlie deformed Paleozoic(?) marble. Conglomerates below and within a thick sequence of quartzite are similar to those in the Fairview Valley Formation in that they contain clasts of marble, calc-silicate hornfels, quartzite, and volcanic rock (Fig. 6). Conglomerate above the quartzite contains volcanic clasts. Cameron et al. (1979) and Miller and Cameron (1982) correlated the quartzite in the Cave Mountain sequence with the Aztec Sandstone, but Walker (1987) correlated it with Lower Triassic sequences on the basis of similarities of composition and sedimentary structures, such as low-angle cross-stratification, that indicate shallow-water deposition. The age of the Cave Mountain sequence is unknown, and we propose that the volcanic-clast conglomerates may be equivalent to the top of the Rodman Mountains "Aztec" sequence and that the quartzite and possibly some of the marble and calc-silicate rock may correlate with Jurassic sequences farther west (Fig. 6). This interpretation is consistent with the observation that all of the dated volcanic rocks in the vicinity that would be likely sources for the conglomerates are Jurassic, not Triassic or Permian, in age. Therefore, we agree with the correlation of the Rodman Mountains and Cave Mountain sequences (Miller and Cameron, 1982), and we further suggest correlation with the Fairview Valley Formation.

Eolian quartz arenite associated with arc-type volcanic rocks occurs in the Cowhole Mountains (Fig. 1) where it has been correlated with the Aztec Sandstone (Marzolf, 1980; Novitsky-Evans, 1978). Volcanic rocks intercalated with and overlying the eolianite sequence are dated as 172 $\pm$ 6 to 167 $\pm$ 4 Ma (U-Pb, zircon; Busby-Spera et al., 1989, Busby et al., this volume) and are thus within error of and younger than the lowest dated ignimbrite in the Sidewinder Volcanic series (180 Ma), which interfingers with and overlies quartzite and quartzose sandstones. The quartz arenite in the Cowhole Mountains is more likely age equivalent to the Temple Cap or Carmel Formations (Busby et al., this volume).

PALEOGEOGRAPHIC AND TECTONIC IMPLICATIONS

Three aspects of our results are important to understanding the paleogeography of the early Mesozoic convergent margin. First, shallow-marine conditions existed in the central Mojave block during late Early to early Middle Jurassic time. The Victorville area appears to record entirely shallow-marine deposition of the quartz arenites, while areas to the east were locally above sea level and received eolian sand. Second, if all of the shallow-marine sequences from Victorville to Cave Mountain are Jurassic instead of Triassic, marine conditions were fairly widespread within the arc until as late as Middle Jurassic time. Third, the geochronologic, sedimentologic, and stratigraphic data suggest a period of uplift and erosion or nondeposition extending from the Early Triassic into the Early Jurassic. These conditions may have reflected relict highlands remaining from Permian deformation (e.g., Stone and Stevens, 1988; Walker, 1988) or some as-yet-unrecognized Triassic deformation similar to that proposed for southeastern California and Arizona (Reynolds et al., 1989). These characteristics of the paleogeography, together with the structural evolution of the region, suggest that the change from high-standing to low-standing paleogeography reflects a large-scale tectonic control on relative sea level that we interpret as the beginning of a period of intra-arc extension or transtension.

Paleoelevation of the Jurassic arc and backarc

The occurrence of craton-derived quartz sand in shallow-marine rocks of the upper Fairview Valley Formation and within the Sidewinder Volcanic series implies that the Mojave segment of the arc was low standing and possibly undergoing active subsidence during early Mesozoic time (Miller and Carr, 1978; Karish et al., 1987; Busby-Spera, 1988). Our new results and correlations also imply that this part of the arc was near sea level in late Early or early Middle Jurassic time. Despite the uncertainty in the age of the lower part of the Fairview Valley Formation, it is evident from the gradational nature of the upper contact that volcanism began prior to or shortly following the end of shallow-marine deposition. Although the Sidewinder Volcanic series were subaerially deposited (Schermer and Busby, 1994), it seems likely that the area remained low-standing at least until after the oldest (Jsl1) volcanic units were erupted because craton-derived quartz sands continued to be an important source for the early intra-arc sediments even in areas outside of calderas, such as at Quartzite Mountain (Schermer and Busby, 1994).

Sedimentologic data from the Victorville region indicate that craton-derived quartz sands gained access to this shallow-marine segment of the arc, similar to the deeper-marine and subaerial segments (Busby-Spera, 1988). We suggest correlation of the shallow-marine facies in the central Mojave block (Victorville area, Rodman Mountains, and Cave Mountain) with Lower Jurassic marine quartz arenites and volcanic rocks that are shallow-marine facies in the southern Sierra Nevada (Busby-Spera, 1984) and deep-marine facies in the northern Sierra Nevada (Fisher, 1990). Early and Middle Jurassic eolianites are also interstratified with subaerial arc-type volcanic rocks in southeastern California and Arizona (see summaries in Busby-Spera, 1988; Saleeby and Busby-Spera, 1992).

The age constraints on the quartzose sandstones suggest that the arc may provide a more complete record of Jurassic quartz arenite deposition than the backarc. Our age of 179.5 ± 3.0 Ma corresponds to the boundary between the Early and Middle Jurassic, at 180 ± 4 Ma (Gradstein et al., 1994) and permits correlation with the Aztec and Navajo Sandstones (Pliensbachian–Toarcian or Aalenian; Peterson, 1994), but not with the Temple Cap Sandstone, which is well dated at 170 ± 1 Ma (Kowallis et al., 2001). In the backarc at this time, a period of removal and/or nondeposition of the eolianites is recorded by the J1 unconformity on the Colorado Plateau (Peterson and Pipiringos, 1979). Although contacts are uncertain at Iron Mountain because of deformation, quartzite intercalated with the Hodge volcanics may be depositionally related, suggesting that quartz sand continued to gain access to the arc as late as ca. 164 Ma (Boettcher and Walker, 1993).

The conformable nature of the Fairview Valley–Sidewinder contact over ~20 km along strike and the occurrence of fine-grained sedimentary rocks along much of this length suggest relatively little tilting during this time. Nonetheless, the presence of volcanic breccias and conglomerates with Paleozoic limestone clasts suggests relief due to both volcanic and tectonic activity. The limestone-cobble conglomerates were previously interpreted as intra-orogenic deposits derived from relief created during Permian–Triassic deformation (Miller, 1978b, 1981; Walker, 1988). Alternatively, the conglomerates could record Jurassic deformation. A third possibility is that there are major problems in the Permian–Triassic time scale, and the conodonts in the Fairview Valley Formation are not reworked; in this case, deposition of the formation would have to have spanned Early Triassic through early Middle Jurassic time with no apparent breaks. This possibility would suggest the unlikely scenario of ~60 m.y. of quiet, shallow-marine deposition during a time when much tectonic activity was occurring elsewhere along the arc and in the backarc (e.g., Burchfiel et al., 1992; Saleeby and Busby-Spera, 1992, and references therein).

Mesozoic tectonics of the Mojave Desert and adjacent regions

The tectonic setting of the Mesozoic arc and backarc and the influence of deformation on paleogeography have been the subject of much controversy. Early workers considered much of the Mesozoic tectonism in the Mojave Desert to be contractional, with major thrusting occurring at several different times throughout the Triassic, Jurassic, and Cretaceous (e.g., as summarized by Burchfiel and Davis, 1981). Preservation of thick volcanic sequences and craton-derived quartz arenites has been attributed to extension (Busby-Spera, 1988) or shortening and transpression (Walker et al., 1990a, 1990b; Dunne et al., 1998), and there is evidence for both extensional and contractional structures in intra-arc, arc-flank, and backarc settings.

Evidence for Jurassic shortening. The East Sierran thrust system in the Inyo Mountains, Slate Range, and its continuation into the Mojave block (e.g., Tiefort Mountains, Cronese Hills, western Mojave block; Fig. 1) appears to be late Early to Late Jurassic in age (Dunne, 1986; Dunne et al., 1978, 1998; Dunne and Walker, 1993; Glazner et al., 1994; Walker et al., 1990a, 1990b). The best-dated Jurassic shortening in the Mojave block involves southeast-vergent ductile thrusting in the Cronese Hills, between 166 ± 3 and 155 ± 1 Ma as shown by U-Pb dating of pre- and postkinematic plutonic units (Walker et al., 1990a). Southeast-vergent shear movement in the Tiefort Mountains is bracketed between ca. 164 and 148 Ma and is interpreted to be related to the East Sierran thrust system (Schermer et al., 2001). Middle Jurassic east-vergent thrusting occurred east (i.e., inboard) of the study area, in the Clipper Mountains, at ca. 161 ± 10 Ma, (Howard et al., 1995; McCaffrey et al., 1991). Age constraints on most of the other thrusts previously inferred to be Triassic and Jurassic show that these are Permian (Last Chance thrust system; Snow, 1992) and middle Cretaceous (Keystone–Clark Mountain thrust system; Fleck and Carr, 1990; Fleck et al., 1994).

Other structures in the Mojave block inferred to be part of the East Sierran thrust system have less-certain kinematics and/or timing. At Iron Mountain, Boettcher and Walker (1993) interpreted contractional deformation to be bracketed by U-Pb dating of ca. 164 Ma prekinematic Hodge Volcanics and 151 ± 11 Ma postkinematic granite. However, structural orientations and metamorphic grade are different in pre-Mesozoic and Mesozoic rocks, suggesting that northwest-southeast shortening may instead have occurred in Paleozoic (Permian?) time. Structures in the Jurassic volcanic rocks are parallel to those inferred by Boettcher and Walker (1993) to be post–148 Ma and could instead be interpreted to be related to a Cretaceous deformational event; kinematics of those structures suggest strike-slip deformation. In the Shadow Mountains, west-vergent folding and fabrics that predate the intrusion of 148 Ma gabbro are also considered to be Jurassic, but poor age constraints also permit the interpretation of Permian deformation (Martin and Walker, 1991). Although the source of coarse debris in the lower Fairview Valley Formation could be related to the belt of Jurassic shortening, the deformation would have had to begin by Early Jurassic and/or Triassic time.

Evidence for extension. Recent work suggests that at the same time that shortening occurred across the East Sierran thrust system, adjacent areas were subject to north-south or northwest-southeast extension (Schermer, 1993). McKenna et al. (1993) inferred that east-west extension in the Panamint Mountains, north of the Garlock fault, is Jurassic (pre–Late Jurassic) in age. In the Cowhole Mountains, Wadsworth et al. (1995) documented northwest-southeast extension, and new age constraints bracket the extension to between ca. 172 and 164 Ma (Busby et al., this volume). In the Providence Mountains, Miller et al. (1994) reported pre–165 Ma east-west extension. The timing of the main phase of north-south extension in the Victorville region is interpreted herein to be ca. 151 Ma, although evidence for minor tilting between eruptions of the ignimbrites in the lower part of the Sidewinder Volcanic Series (i.e., between Jsl1 and Jsl2 and between Jsl3 and Jsl4) may suggest earlier extension.

Implications for plate-tectonic regime and paleogeography. The tectonic significance of Jurassic deformation in the Mojave Desert is controversial. In contrast to the arc-flank setting of the Inyo Mountains, deformation in the Mojave Desert was clearly in an intra-arc setting, as evidenced by the long time span and large volume of volcanic rocks and broadly coeval plutonic rocks (Miller and Busby, 1995). The mode of preservation of volcanic rocks in the Inyo Mountains—arc-flank sequences preserved in the footwalls of thrusts (Dunne and Walker, 1993; Dunne et al., 1998)—cannot apply to areas where contraction was either older or not present. Furthermore, thick volcanic sequences in the Mojave Desert are generally separated from areas of thrusting by many kilometers (Fig. 1). Calderas were the primary mode of preservation of most of the Lower Sidewinder volcanic series (Schermer and Busby, 1994). Our new data on the age of major tilting and extension (151 Ma) show that the mapped normal faults are too young to have been the cause of initial subsidence in the Victorville region. This determination does not preclude an earlier phase of extension during deposition of the Fairview Valley Formation and eruption of the earliest ignimbrite, but there are no dated Early Jurassic or Triassic structures in the region. Normal faulting and tilting of the Lower Sidewinder volcanic series shortly after eruption of the youngest ignimbrite, combined with transtension during emplacement of the Independence dike swarm and Upper Sidewinder volcanic series, probably enhanced preservation of the volcanic rocks (Schermer, 1993; Schermer and Busby 1994).

The apparent continuity and broad consistency of timing of the East Sierran thrust system has been interpreted to indicate that the arc was contractional (Walker et al., 1990a, 1990b), and some workers have argued that shortening was limited to the Middle Jurassic and entirely predates Late Jurassic extension (Miller et al., 1994; Howard et al., 1995). However, in the areas described herein, there is no systematic overprinting of extensional structures on contractional [***Author: Here, you already had "contractional."] ones (or vice versa), and age constraints permit simultaneous shortening and extension (e.g., Cowhole Mountains and Cronese Hills). Analysis of the spatial and temporal relationships suggest that the two regimes may have been broadly coeval but spatially distinct in late Middle to Late Jurassic time (Schermer, 1993). Coeval north-south to northwest-southeast extension and east-west shortening within the arc have been interpreted to be due to a sinistral oblique subduction regime (Saleeby and Busby-Spera, 1992; Schermer, 1993; Schermer and Busby, 1994; Schermer et al., 2001). The emplacement of the Independence dike swarm in Late Jurassic time has also been previously recognized to be related to sinistral transtension and/or transpression (Glazner et al., 1999; Moore and Hopson, 1961). The Independence dike swarm and coeval extension in the Victorville region appear fairly limited in time (ca. 152–148 Ma); however, if the swarm spans as much as 10 m.y. (Carl et al., 1998), it would overlap the timing of east-west shortening in the Mojave, suggesting a longer period of sinistral shear. Extensional regions within this oblique-subduction regime may have been subsiding; the widespread nature of the low paleoelevation inferred here would then suggest that much of the southern part of the arc was extensional.

CONCLUSIONS

Stratigraphic, sedimentologic, and geochronologic data from the Victorville region of the Mojave Desert indicate the Fairview Valley Formation, previously considered to be Early Triassic, is at least in part Early Jurassic in age. The area may have been high and erosional from Permian until the Early Jurassic; coarse debris near the top of the Fairview Valley Formation could be related to Mesozoic rather than Permian deformation. A gradational contact between shallow-marine rocks of the Fairview Valley Formation and Sidewinder Volcanic Series indicates that shallow-marine conditions existed at the beginning of arc volcanism. Similar sequences in the Rodman Mountains and at Cave Mountain contain associated eolianites, suggesting a coastal environment. Subaerial explosive volcanic activity began at 179.5 ± 3.0 Ma and continued until 151 ± 1.3 Ma (lower Sidewinder Volcanic Series). A U-Pb date of 152 ± 6 Ma on a rhyolite dike of the Independence dike swarm (upper Sidewinder Volcanic Series) that postdates normal faulting and tilting of the ignimbrite sequence limits the age of extension in this region to ca. 151 Ma. These data suggest that the Victorville area underwent transtension- or extension-related subsidence during the Late Jurassic. We interpret the regional pattern and timing of deformation to suggest that the Mojave segment of the arc underwent approximately east-west shortening and approximately north-south extension related to sinistral oblique subduction during late Middle to Late Jurassic time.

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