# Jurassic magmatism in the central Mojave Desert: Implications for arc paleogeography and preservation of continental volcanic sequences

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## ABSTRACT

**Exposures of Jurassic magmatic rocks in the west-central Mojave Desert provide insight into the changing character of volcanism throughout Jurassic time and the paleogeography of the continental arc. Middle Jurassic explosive volcanism (Lower Sidewinder volcanic series) resulted in collapse of multiple calderas. This was followed by north-south extension broadly coeval with batholith emplacement. Late Jurassic effusive volcanism (Upper Sidewinder volcanic series) appears to reflect transtension over a larger region during intrusion of the Independence dike swarm.**

**The Lower Sidewinder volcanic series consists of a subaerial, nested caldera complex with an aggregate thickness of >4 km. The first caldera formed during the eruption of crystal-poor rhyolite ignimbrite. Outflow and intracaldera facies are intercalated with quartzose sandstone of probable cratonal provenance. The second caldera formed during the eruption of crystal-rich rhyolite to dacite ignimbrite. This ignimbrite exhibits complex mineralogical zoning and contains two units of probable collapse-related mesobreccia within the 1,400-m-thick intracaldera sequence. A third caldera, nested within the second, is filled with crystal-rich biotite-dacite ignimbrite and tuff breccia. A fourth caldera, largely coincident with the second, formed during eruption of lithic- and pumice-lapilli dacite ignimbrite. Eruption and collapse appear to have been multistage, as several units of reworked tuff and fallout tuff occur within the 1,750-m-thick intracaldera sequence, and caldera collapse breccias occur at the base and near the middle of the sequence. The top of this sequence contains reworked tuffs and epiclastic rocks, suggesting that the fourth caldera provided a posteruptive depocenter for accumulation of sediment.**

**Normal faulting, tilting, and erosion followed explosive volcanism and was broadly contemporaneous with intrusion of Middle Jurassic porphyritic quartz monzonite plutons. Plutons and tilted Lower Sidewinder volcanic series are intruded and unconformably overlain by latest Jurassic volcanic rocks (Upper Sidewinder volcanic series). The Upper Sidewinder volcanic series is characterized by alkalic basalt to basaltic andesite and rhyolite lavas, hypabyssal intrusions, and dikes, including the 148 Ma Independence dike swarm. Regional northeast-southwest extension is suggested by the presence of the northwest-striking dike swarm and by bimodal volcanism. The absence of debris-flow deposits and epiclastic rocks suggests an intra-arc region of low relief.**

**Although local caldera-related subsidence was the principal control on accumulation of Lower Sidewinder volcanic rocks, preservation was likely enhanced by Middle Jurassic extension. Late Jurassic extension was of broader regional extent but lesser magnitude because it did not create basins or cause significant tilting of strata. The geometry, timing, and regional setting of Middle and Late Jurassic extension and magmatism suggest a sinistral oblique subduction regime for the Jurassic arc of the southern U.S. Cordillera.**

## INTRODUCTION

Volcanologic, sedimentologic, and structural characteristics of intra-arc basins can be used to infer arc paleogeography and tectonic evolution because such basins record much of the geologic history of volcanic arcs. The scale and origin of these basins may vary depending on the structural and thermal regime of the arc; the types of deposits and facies relations depend on the character of volcanic centers and local and regional paleogeography. In continental arcs, high-standing volcanoes may be quickly eroded, leaving sparse primary eruptive products preserved in the geologic record. In arcs undergoing subsidence, however, volcanic centers and their surrounding deposits may be well preserved.

Subsidence within arcs can occur on a variety of scales, from the local scale (tens of kilometers) related to caldera formation and extension above plutons, to the regional scale (hundreds of kilometers), reflecting extension along and across the volcanic arc (Busby-Spera and others, 1990b). Preserved thick volcanic and sedimentary successions in the early Mesozoic arc of the southwestern Cordillera, as well as the interstratification of mature, craton-derived eolian quartz arenites with vent-proximal volcanic facies, have led several workers to postulate that the arc was extensional or neutral, and low-standing (Miller, 1981; Karish and others, 1987; Busby-Spera, 1988; Fisher, 1990; Riggs and others, 1993). Busby-Spera (1988) speculated that the Sierran and Mojave-Sonoran segments of the early Mesozoic Cordilleran arc occupied a 1,000-km-long graben depression, similar to the modern extensional arc of Central America (Burkart and Self, 1985). Solomon and Taylor (1991) interpreted oxygen isotope data from Jurassic plutons along the length of the proposed graben depression to reflect emplacement in a rift environment. Early to middle Mesozoic contraction, however, has been documented along the eastern Sierran region and southward into the Mojave Desert (for example, Dunne, 1986; Schweickert and Lahren, 1987; Walker and others, 1990a; Dunne and Walker, 1993), leading some workers to infer that the preservation of volcanic rocks was due to their protected position in the footwalls of thrust faults (Dunne, 1986; Walker and others, 1990a).

A relatively continuous record of Mesozoic arc magmatism is preserved in the west-central Mojave Desert. The earliest plutonic rocks record the late Permian–Triassic initiation of this segment of the Cordilleran

Geological Society of America Bulletin, v. 106, p. 767–790, 13 figs., 3 tables, June 1994.

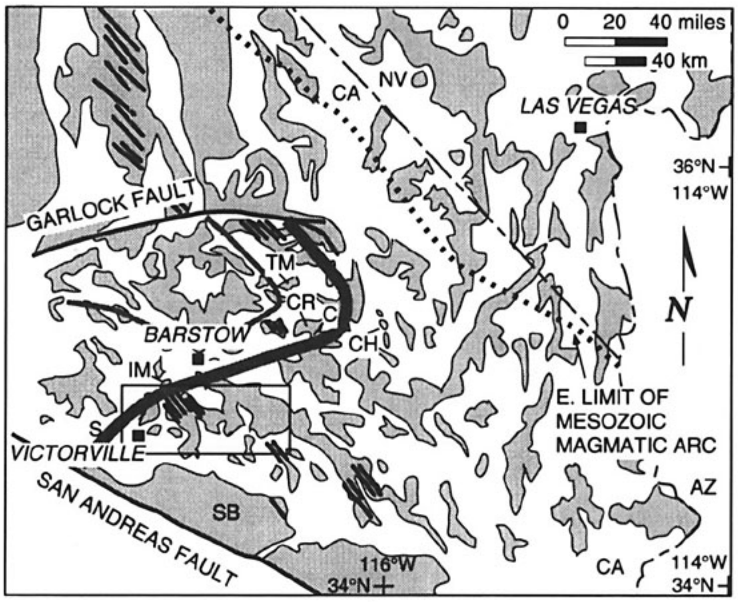



**Figure 1. Ranges of the Mojave Desert and adjacent regions showing location of study area, location of Figure 2, and distribution of the Independence dike swarm (after James, 1989). Localities referred to in text: C = Cave Mountain; CH = Cowhole Mountains; CR = Cronese Hills; IM = Iron Mountain; KH = Kramer Hills; S = Shadow Mountains; SB = San Bernardino Mountains; TM = Tiefort Mountain. Thick shaded line indicates position of miogeoclinal-cratonal hingeline, and thin shaded line indicates miogeoclinal/eugeoclinal boundary, after Martin and Walker (1991).**

arc, and magmatism continued episodically through Late Cretaceous time (Hamilton, 1978; Miller, 1978; Burchfiel and Davis, 1981). In this paper, we describe thick Triassic(?) through Jurassic volcanic and sedimentary sequences in the west-central Mojave desert (the Sidewinder volcanic series) that were preserved due to active subsidence within the arc, both on local and regional scales.

### Geologic Setting of the Central Mojave Desert

The Mesozoic arc in the Mojave segment of the Cordillera was built on cratonal to miogeoclinal and eugeoclinal facies of the truncated Paleozoic continental margin (Fig. 1). Permo-Triassic plutonism, Triassic through Jurassic shallow marine to terrestrial sedimentation and volcanism, and voluminous Middle Jurassic and Late Cretaceous plutonism characterize the evolution of this part of the arc (Burchfiel and Davis, 1972, 1981; Miller and Cameron, 1982; Stone and Stevens, 1988; Walker, 1988).

The west-central Mojave Desert, as considered herein, includes the area between Quartzite Mountain north of Victorville, and the Rodman Mountains southeast of Barstow (Figs. 1 and 2). The stratigraphy of late Precambrian to Paleozoic rocks indicates that this region was part of the transitional cratonal/miogeoclinal realm until latest Paleozoic time (Bowen, 1954; Stewart and Poole, 1975; Cameron, 1981; Miller, 1981; Brown, 1983). Latest Paleozoic contraction in the region was broadly synchronous with the emplacement of alkalic plutons related to the initiation of the magmatic arc (Miller, 1978) and may have resulted from sinistral truncation of the continental margin (Burchfiel and Davis, 1972, 1975, 1981; Miller, 1981; Walker, 1987, 1988). Lower Triassic(?) to Jurassic rocks unconformably overlie deformed Paleozoic rocks in the area from Victorville to Cave Mountain (Fig. 1; Cameron and others, 1979; Miller, 1981; Walker, 1988). In the Victorville region, this sequence includes the Lower Triassic(?) shallow marine or lacustrine Fairview Valley Formation (Miller, 1978, 1981), Jurassic eolian quartz arenite (Aztec sandstone; Miller and Carr, 1978), and the Sidewinder volcanic series (Bowen, 1954) of Middle and Late Jurassic age (Schermer, Mattinson, and Busby, unpub. U-Pb zircon data).

The Sidewinder volcanic series comprises the majority of the Mesozoic supracrustal rocks in the west-central Mojave desert. The rocks were first studied by Bowen (1954) and mapped by Dibblee (1960b, 1960c, 1964a, 1964b). In a detailed study of the Ord and Fry Mountains (Fig. 2), Karish and others (1987) recognized two distinct ages of volcanic rocks within the Sidewinder volcanic series, including (a) pyroclastic rocks of the Lower Sidewinder volcanic series and (b) lavas and dikes of the Upper Sidewinder volcanic series, which were postulated to be the southern extension and eruptive equivalents of the Late Jurassic (148 Ma) Independence dike swarm (Fig. 1; Smith, 1962; James, 1989). Middle Jurassic plutonic rocks intrude the Lower Sidewinder volcanic series; Upper Sidewinder volcanic rocks were interpreted to unconformably overlie the plutons and Lower Sidewinder volcanic series at Ord Mountain (Karish and others, 1987).

Much of the Mojave region was intruded by voluminous Late Cretaceous plutons, and K/Ar data are interpreted to indicate a strong thermal pulse in the southern Mojave region at ca. 70 Ma (Miller and Morton, 1980). Late Cretaceous thrusting in the western Mojave (for example, Rand thrust) may record large-scale displacement (Jacobsen and others, 1988; Silver and James, 1989), but rocks in the area shown in Figure 2 are interpreted to have behaved as a coherent block during Cretaceous time (Karish and others, 1987). Tertiary extension occurred in the Mojave extensional belt to the north of the region shown in Figure 2 (Dokka and Woodburne, 1986; Glazner and others, 1988; Dokka, 1989), but no extension-related Tertiary rocks are exposed in the study area (for example, Bortugno and Spittler, 1986). Mesozoic rocks there probably were not deformed during Tertiary extension (Dokka, 1989), although they may have been displaced westward as a coherent block relative to volcanic rocks farther north (Glazner and others, 1988; Martin and others, 1993). Late Cenozoic dextral faults related to the San Andreas fault system in part control the present physiography, but cumulative displacements on these faults (Helendale, Lenwood, and Camp Rock faults; Fig. 2) apparently do not exceed 10–15 km (Dibblee, 1961; Dokka, 1983; Dokka and Travis, 1990). Thus, Cenozoic structural dismemberment of Mesozoic volcanic and structural features in the study area has been minimal.

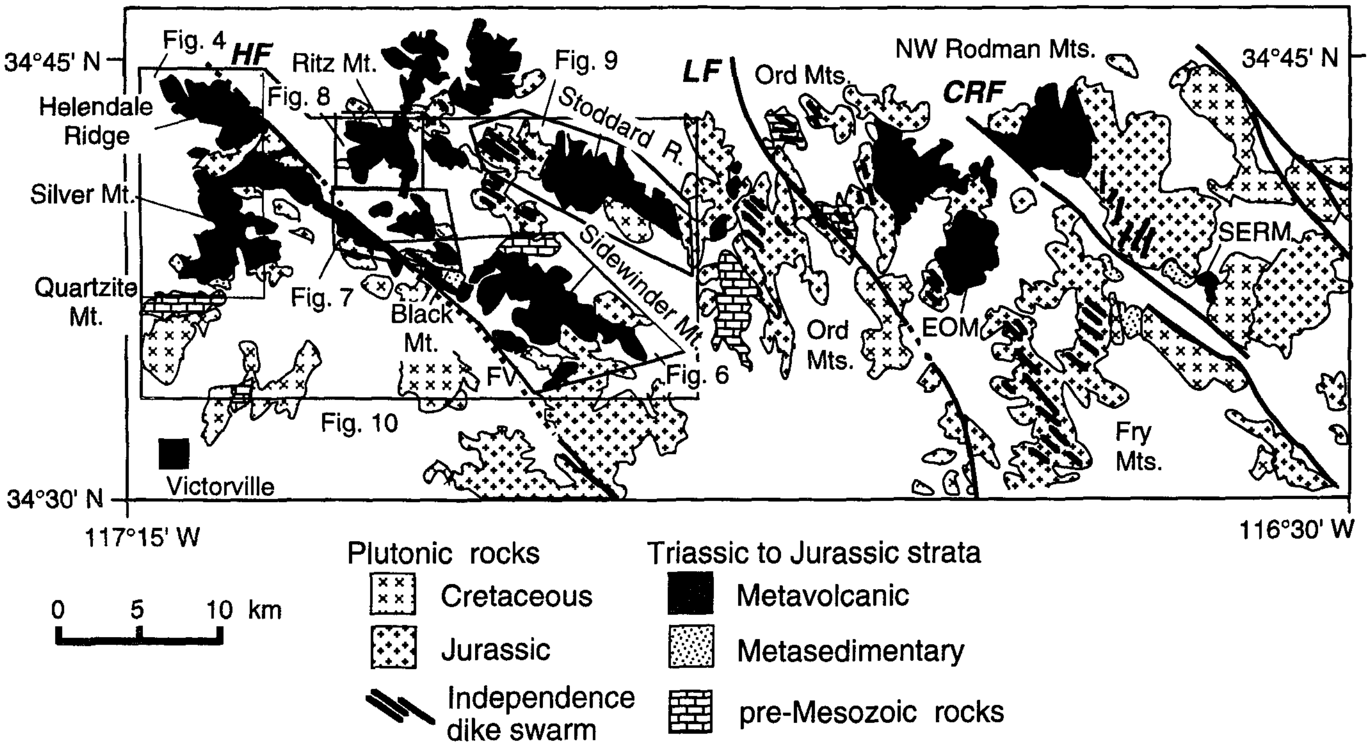



**Figure 2. Generalized geologic map of the west-central Mojave Desert, after Karish and others (1987). Abbreviations of localities: FV = Fairview Valley; EOM = East Ord Mountain; SERM = southeast Rodman Mountains. Ritz Mountain and Helendale Ridge are informal names. Late Cenozoic dextral faults: HF = Helendale fault; LF = Lenwood fault; CRF = Camp Rock fault. Boxes show location of maps in Figures 4, 6, 7, 8, 9, and 10.**

### Methods and Terminology

Maps at a scale of 1:12,000 to 1:24,000, stratigraphic sections, and petrographic and structural data form the basis for our paleogeographic and tectonic interpretations of the Mesozoic arc in the west-central Mojave region. U-Pb (zircon) geochronology of the Jurassic volcanic and plutonic rocks is described elsewhere (Graubard and others, 1988; Schermer, Mattinson, and Busby, unpub. data), and the structural evolution is described in detail in Schermer (1993). Mesozoic supracrustal rocks in the region are typically subgreenschist to lower greenschist facies and retain abundant primary volcanic and sedimentary textures and structures, including relict (devitrified) glass shards and pumice. Potassium metasomatism and albitization have variably affected groundmass and feldspar compositions. Although metamorphic recrystallization is locally intense adjacent to intrusions, it is in general sufficiently weak that we drop the prefix *meta* in reference to rock types.

Mesozoic volcanic rocks in the study area were named "Sidewinder volcanic series" by Bowen (1954). We retain the term *series* for consistency with previous work, although, as noted by Miller (1978, 1981), the term *series* is not appropriate inasmuch as these rocks are now known to comprise two distinct ages of volcanic rocks, separated by a period of deformation, pluton intrusion, and erosion (Karish and others, 1987; this study). We have given informal names to the widespread ignimbrite units for ease of discussion but retain map symbols that reflect their stratigraphic positions. Table 1 and Figure 3 together serve as an explanation for the maps and stratigraphic columns (Figs. 4, 5, 6, 7, 8, 9, 10). The terminology for pyroclastic rocks used herein, after Sparks and others (1973) and Fisher and Schminke (1984), is given in Table 1.

### Recognition of Eruptive Centers

Recognition of eruptive centers in the Mesozoic arc is difficult owing to posteruptive faulting, pluton intrusion, and erosion. Original topographic features are not preserved, but several kilometers of structural relief are exposed as a result of faulting. Criteria for recognition of calderas include the following: (1) Thick ignimbrite (several hundred meters to >1 km) that is petrographically similar throughout the section and contains no interstratified sedimentary rocks or internal erosional surfaces is inferred to reflect intracaldera subsidence during eruption, in contrast with typically much thinner (meters to tens of meters) outflow ignimbrites (Christiansen, 1979). (2) Megabreccia or mesobreccia consisting of clasts of country rock encased in ignimbrite are inferred to result from slumping of the topographic wall during catastrophic caldera collapse (Lipman, 1976). (3) Locally preserved, steeply dipping structural boundaries intruded by hypabyssal bodies and pyroclastic dikes are commonly inferred to represent ring fractures around the margin of a caldera where venting occurred (for example, Smith and Bailey, 1968; Reedman and others, 1987).

Features used for recognition of vent and vent-proximal facies in stratovolcanoes include (1) close association of hypabyssal intrusions and lava flows, for example, dikes that feed lava flows, and (2) breccias composed of clasts of country rock and/or hypabyssal intrusions in a matrix of intrusive material.

TABLE 1. FIELD, PETROGRAPHIC, AND TEXTURAL CHARACTERISTICS OF PRINCIPAL ROCK TYPES IN THE WEST-CENTRAL MOJAVE DESERT

| Map unit | Field characteristics* | Phenocryst and groundmass mineralogy of igneous units |
|---|---|---|
| Kqm | Cretaceous(?) quartz monzonite. Brown-tan massive rounded weathering semiresistant outcrops. Med-cse gr equigranular, gray-white on fresh surface. Does not contain tectonic foliation. | Subequal proportions Kspar, plag; quartz varies ~5%–30%. Biotite 2%–5%. |
| fbr | Flow-banded aphanitic rhyolite hypabyssal intrusions, dikes, and lava flows. Commonly form tan or reddish-brown stained resistant outcrops, tan to light gray on fresh surface. Local lithophysal structure. | Aphyric; groundmass recrystallized quartz and Kspar. |
| sf | Hypabyssal rhyolite intrusive rocks, occur as subvertical dikes 1–100 m wide and irregularly shaped bodies. Forms white to pale gray fractured outcrops. Locally flow-banded and brecciated near margins. | Phenocrysts: ~0%–20%; typically contains ≤5% plag up to 2 mm; some dikes with rare qtz, up to 15% Kspar. Groundmass generally recrystallized qtz + Kspar ± plag. |
| dpp | Pale to dark purplish gray porphyritic hypabyssal intrusive and probable extrusive rocks. Locally flow-banded and brecciated near margins, locally as peperitic intrusions into fine-grained sandstone. | ~3%–7% plag phenocrysts 1–2 mm in recrystallized and altered groundmass. |
| Jsub | Basalt to andesite intrusive and extrusive rocks. Forms dark greenish black resistant outcrops and cliffs. Basal flows locally contain angular to subangular lithic fragments of Jslo up to 20 cm and are intercalated with planar bedded tuffaceous siltst-cse sst; local peperitic contacts with sst occur. Lavas are commonly vesicular. Intrusive rocks occur as dikes 1–20 m wide and irregular bodies. Highly variable texture from coarse-grained porphyry to fine grained, locally with two size populations of plag phenocrysts, ~1–2 mm and 10–20 mm. | Phenocryst content highly variable, ≤5%–25% plag 1–20 mm, 3%–4% cpx ~1 mm. Groundmass: fine-grained plag + cpx. Vesicles commonly filled with coarse-grained epidote. |
| pf | Felsic porphyry, occurs as hypabyssal intrusions, dikes, and border phases of J?qm. Light to medium gray with distinctive coarse gray Kspar phenocrysts. Locally flow-banded. | 5%–20% phenocrysts 2–6 mm include Kspar + plag ± qtz in a fine-grained to microcrystalline groundmass composed of recrystallized qtz, Kspar, and plag. Locally up to 1% biotite. Kspar: plag ratio of phenocrysts varies, but groundmass generally suggests granite-qtz monzonite composition. |
| J?qm | Jurassic(?) quartz monzonite and granite, medium to cse grained, commonly porphyritic with coarse gray or purplish gray euhedral Kspar phenocrysts; heterogeneous composition with hbl diorite, gabbro, and monzonite bodies as inclusions and border phases. Locally contains well-developed tectonic foliation, locally developed magmatic foliation. | Qtz 10%–50%, Kspar 20%–40% plag 15%–30%, qtz and plag up to 4 mm; ksp up to 10 mm. Fine to cse gr biotite 0%–20%, med-cse gr hbl 0%–5% in granite, qtz monzonite; up to 35% in diorite and gabbro. Sphene is ubiquitous as accessory phase, zircon common. |
| Jslu<br>Jsluh<br>(tuff of Ord Mt.) | Latite ignimbrite, age relative to other Jsl unknown. Forms massive dark gray cliffs; purplish gray-gray on fresh surface. Massive to eutaxitic, locally up to 20% flattened pumice lapilli up to 2 cm × 5 cm. Sparse fine-grained aphyric angular volcanic lithic lapilli generally <1 cm. Pumice compaction decreases upsection. Locally appears to be hypabyssal intrusive (Jsluh) as it lacks broken crystals and pumice. | Ord Mt. (Karish and others, 1987): 20% plag 1–3 mm, up to 2% biotite 1 mm.<br>NW Rodman Mt: 20%–30% plag 1–3 mm, minor biotite, local preservation of recrystallized densely welded shards. |
| Jsl$_4$<br>(tuff of Stoddard Ridge) | Andesite or dacite lithic lapilli ignimbrite, forms dark brown to black resistant ledges and cliffs except where altered. Contains flow units with variable % lithic and pumice lapilli. Typically contains ≥25% lithic fragments of light gray plagioclase porphyry (Jslr) 1–2 cm in diameter, 0%–25% pumice lapilli up to 8 cm, avg 2–4 cm long. Local block-rich horizons with lithics of older ignimbrites 0.5–2 m in diameter. Local pumice-rich rheoignimbrite. Bedded ash-fall tuff and fluvially reworked tuff horizons 1–10 m thick throughout sequence. Local hbl andesite lavas near middle of sequence. Top ~300 m of unit dominantly reworked, consisting of (1) poorly sorted siltstone to pebbly sst in plane to massive beds 3 cm to 50 cm, locally normally graded and scoured at base; (2) matrix-supported, massive to crudely stratified, nonsorted volcanic breccias with rare pumice and typically >40% rhyolite volcanic lithic fragments, interpreted as debris-flow deposits; (3) probable primary ignimbrites with pumice and lithic concentrations typical of the underlying ignimbrite section. | Phenocrysts 6%–20% (avg ~15%, 1 mm) dominantly plag; 0%–5% Ksp, tr-1% biot. Local preservation of recrystallized moderately to densely welded shards; pumice shreds and broken crystals are common. |
| Jslr | Flow-banded to massive rhyolite or rhyodacite porphyry; occurs only at SR and forms medium to dark purplish gray rugged cliffs. Includes flow-banded and massive hypabyssal intrusive facies, flow-banded and brecciated extrusive facies interpreted as dome-related breccias, and inclusions <200–250 m thick of comagmatic? rhyolite porphyry welded ignimbrite. | Phenocrysts 3%–15%: ≤2% qtz ~1 mm, ≤10% Kspar, ~3 mm, ≤5% plag ~1–3 mm. Comagmatic(?) ignimbrite contains ~20% phenocrysts. Groundmass approx. subequal qtz, Kspar, plag. |
| Jsl$_3$<br>(tuff of Turtle Mt.) | Biotite dacite crystal-rich ignimbrite and tuff breccia. Forms nonresistant medium gray outcrops; medium gray to purplish gray on fresh surface; contains ≤5% pumice, sparse lithics, but has local pumice-rich horizons (up to 15%, with pumice up to 6 cm). Tuff breccia is matrix-supported, massive, unsorted, with subangular to subrounded clasts of biotite dacite crystal-rich ignimbrite in a matrix of biotite dacite crystal-rich ash. Up to 80% clasts, up to 1 m, typically ~10–20 cm. Local indistinctly graded and bedded crystal-rich horizons. | Generally >35% crystals, avg 1–2 mm; matrix and clasts same composition: 2%–5% qtz, 1%–3% Kspar, 25%–35% plag, 3%–7% biot, 1%–4% Fe-oxides, ubiquitous euhedral sphene as accessory phase up to 1 mm long; welded shards in matrix and clasts rarely preserved, common broken crystals. |
| sws$_2$ | Volcaniclastic and epiclastic sedimentary rocks. Includes reworked tuff (Jsl$_2$), volcanic lithic pebble cgl, sst, siltst, thin dacitic lithic lapilli tuff, and flow-banded andesite or dacite lavas and flow- or dome-related breccias of angular lava clasts with a sst matrix. Sedimentary rocks thin to medium-bedded, with planar and low-angle crossbedding, local indistinct and graded beds, and scour/fill structure; interpreted as fluvial deposits. Composition dominantly Jsl$_2$ lithic fragments and crystals at base of sequence; upsection includes lavas and other volcanic rocks from outside the Sidewinder sequence. Top of sequence contains intercalated ignimbrites identical to Jsl$_2$, tuff-breccia of Jsl$_3$. | |
| Jsl$_2$,<br>tb,<br>Jsl$_{2b}$<br>(tuff of Sidewinder Mt.) | Rhyolite crystal-rich ignimbrite, typically massive, dark greenish gray at SWM and SR, purplish gray to light gray elsewhere. Pumice typically present, but sparse, moderately flattened, avg ~1–6 cm long, rare altered volcanic lithics. Zoned from rhyolite to dacite; where rhyolitic, coarse pink Ksp and embayed quartz characterize this unit. At SWM tuff breccia horizons (tb) are massive, unsorted, matrix-supported, with subangular to subrounded polymict volcanic lithics 1 cm–1 m in size, including Jsl$_2$ clasts and gray plag-phyric silicic volcanic rocks; matrix typically dacitic Jsl$_2$. Jsl$_{2b}$: Only in fault block at NE SWM, typically lithic and pumice lapilli ignimbrite with matrix as in Jsl$_2$; contains up to 30% pumice lapilli up to 30 cm, up to 25%–30% lithics 3–20 cm; lithics include clasts of Jsl$_2$. Pumice compaction weak to strong. | Groundmass ubiquitously altered and epidotized; recrystallized shards preserved only in Jsl$_{2b}$ and tb matrix, but pumice and broken crystals are common. Crystal content avg 30%, composition varies from rhyolite to dacite: Ksp avg 3–4 mm, 1%–25%; qtz 3–4 mm, 1%–15%; plag 1–2 mm, 10%–30%, biot 1%–7%, 1–2 mm.<br>Jsl$_{2b}$ and tb shards (rare) indicate incipient to dense welding. |
| lts | Andesite lava flows, andesitic lithic lapilli tuffs, volcanogenic sedimentary rocks, welded crystal-poor rhyolite ignimbrite; typically dark to medium purple-gray; local quartzose sandstones. | |
| | Andesite lava flows: aphyric to sparsely plag phyric, massive, altered; locally contain up to 3%–5% volcanic lithic fragments. | Andesite lava: 2%–3% plag, ~1% Fe oxides, quartz-filled vesicles. Groundmass very altered, locally preserved felty plag microlites, minor Kspar. |
| | Andesitic lithic lapilli tuff: up to 15% angular to subrounded fragments of andesite <1 cm–~6 cm; avg 2–4 cm. May grade laterally into andesite lavas. | Lithic lapilli tuff: 20%–40% plag, tr biot, 2%–5% Fe oxides. |
| | Volcaniclastic rocks: intercalated sedimentary rocks, tuffs, and lavas, best exposed at NBM, include poorly sorted volcanic lithic granule sst, and sand-matrix-supported volcanic breccia with heterolithic clasts to 4 cm. Typically 3–20 cm thick planar and lenticular beds, locally scour/fill structure. Local shale (?tuff?) beds to 0.5 cm thick, well-laminated 0.1–0.3 cm thick fine sand, silt, shale may represent subaqueous ash-fall. Intercalated rhyolite lithic lapilli tuff contains 0%–20% pumice, 5%–25% lithic fragments, ~15% crystals. | |

TABLE 1. (*Continued*)

| Map unit | Field characteristics* | Phenocryst and groundmass mineralogy of igneous units |
|---|---|---|
| | Welded rhyolite ignimbrite: contains sparse plag; locally present at or near base of sequence. | Welded ignimbrite: 5%–10% plag 1–2 mm, matrix recrystallized to qtz + Kspar; rounded qtz grains may be detrital. |
| | Quartzose sandstone: includes tan to white massive med-gr sst with <10% to >60% fgr material interpreted as recrystallized rhyolite ash and rounded to well-rounded monocrystalline qtz grains within and at top of $Jsl_1$ at BM and minor gray massive med-cse gr quartz-rich sst at NBM. | |
| $Jsl_1$ (tuff of Black Mt.) | Crystal-poor rhyolite ignimbrite, generally pale green or bleached white, forms highly fractured reddish brown-stained recessive to ledgy outcrops. Pumice lapilli 1%–25%, avg 1–2 cm long; lithic lapilli generally <3% are dominantly silicic and mafic volcanic rock fragments and minor calc-silicate rock, marble, and quartzite; these metasediments are probably derived from Precambrian and Paleozoic country rocks. | Avg <10%–12% phenocrysts ~1 mm, 2%–12% plag; 1%–5% Kspar, tr qtz. Sphene, zircon, apatite as accessory phases. Recrystallized shards commonly well preserved, indicate partial to dense welding. |
| Jsla | Andesite or dacite lava flows and hypabyssal rocks: Massive brown to gray-green porphyritic plagioclase-rich, locally vesicular, largely massive with local flow-breccia. Plagioclase phenocrysts are weakly aligned. | Phenocrysts average 30%–35%: plag 30%–35%, ≤2 mm; cpx ≤5%, ≤2 mm. Locally glomeroporphyritic; plag generally saussuritized. Groundmass typically recrystallized, altered; locally preserved trachytic intergranular plag + cpx. |
| $sws_1$ | Volcaniclastic and epiclastic sedimentary rocks intercalated with ignimbrites of $Jsl_1$; occur mainly in QM area; gradational contact with underlying Fairview Valley formation. | |
| | (a) Matrix-supported volcanic breccias, medium to thick bedded, crudely stratified to nonstratified, nongraded or normally graded, rare scour and fill structures; angular to subangular volcanic and subrounded metasedimentary clasts 1–10 cm, rarely to 25 cm. Intercalated with med to cse-gr volcanic-lithic sst, rare thin tuff? or mudstone beds. Sandstone beds 1–2 m thick, contain indistinct planar lamination and rare low-angle cross-lamination. Volcanic clasts, typically >70%, include intermediate composition plagioclase porphyry, silicic porphyritic and aphyric volcanic rocks. ~10%–30% of clasts are sedimentary; include quartzite, marble, siltstone, mudstone. | |
| | (b) Parallel laminated calcareous siltstone and mudstone, beds 0.2–2.5 cm, intercalated with fine to cse gr volcanic lithic sst and granule sst in beds and lenses up to 60 cm. | |
| | (c) Quartzite and quartzose sst, fine-med grained; where unaltered, exhibit planar lamination. Contains well-rounded monocrystalline quartz grains and no polycrystalline quartz or quartzite lithic fragments. | |

*NBM, N. Black Mt.; NWRM, NW Rodman Mts.; OM, Ord Mt.; QM, Quartzite Mt.; SR, Stoddard Ridge; SWM, Sidewinder Mt.; "ignimbrite," welded or nonwelded material composed predominantly of pumice and shards (Sparks and others 1973). Tuffs are named following Fisher and Schminke (1984): "tuff," pyroclastic rocks with >75% fragments <2 mm in size; "pumice lapilli tuff," 25%–75% pumice fragments 2–64 mm in size; "lithic lapilli tuff," 25%–75% lithic fragments 2–64 mm in size; "tuff breccia," 25%–75% fragments >64 mm; "breccia," >75% fragments >64 mm.

## MESOZOIC MAGMATISM AND SEDIMENTATION, WEST-CENTRAL MOJAVE DESERT

In this section we briefly summarize the paleogeography during the initiation of arc volcanism in the region and describe (1) explosive volcanism and caldera formation during eruption of the Lower Sidewinder volcanic series, (2) postcaldera faulting and pluton intrusion, and (3) Upper Sidewinder effusive volcanism.

### Paleogeography During the Initiation of Arc Volcanism

The oldest Mesozoic sedimentary rocks in the west-central Mojave, the Fairview Valley Formation (Bowen, 1954; Dibblee, 1960b, 1960c; Miller, 1978, 1981), provide information about the paleogeography of the region during the early stages of Cordilleran magmatic arc evolution. These strata, consisting of >1,000 m of calcareous siltstone, limestone, and limestone cobble conglomerate, are exposed at Quartzite Mountain, Black Mountain, and in the Tricolor Quarry area of Sidewinder Mountain (Figs. 2 and 3). The Fairview Valley Formation was interpreted by Miller (1978, 1981) to reflect deposition in alluvial fan and shallow marine or lacustrine environments. The contact between the Fairview Valley Formation and the overlying Sidewinder volcanic series has been interpreted as disconformable (Miller, 1978, 1981), conformable (Walker, 1987), or faulted (Graubard and others, 1988). We have identified a sequence that shows a conformable, gradual transition between shallow marine(?) Fairview Valley deposition and Sidewinder volcanic arc magmatism (Schermer and Busby-Spera, 1990 and unpub. data).

The transition between the Fairview Valley Formation and Sidewinder volcanic series is marked by volcaniclastic and quartzose sedimentary rocks (unit $sws_1$, Table 1; column 1, Fig. 3). Polymict volcanic breccias record arc volcanic activity in the region. The quartzose sandstones contain 50%–90% well-rounded, monocrystalline quartz of medium to fine grain size in a calc-silicate matrix (Miller, 1981; our unpub. data); polycrystalline quartz, quartzite lithic fragments, and bipyramidal volcanic quartz are absent. The supermature character of the quartz grains suggests distant, rather than local, derivation. We suggest that these far-traveled quartz grains were derived from the cratonal back-arc region of the Western Interior, which was repeatedly covered with extensive sheets of windblown sand during the Jurassic (Peterson, 1988).

We concur with Miller (1978, 1981) that the Fairview Valley Formation was deposited in a shallow marine or lacustrine environment, with local alluvial fan facies. The top of the Fairview Valley Formation is tentatively interpreted as a marginal marine facies correlative with calcareous sedimentary rocks that are intercalated with and overlie eolian quartz arenite (Aztec sandstone) in the Rodman Mountains (Miller and Carr, 1978) and the Cowhole Mountains (Novitsky-Evans, 1978). The Aztec sandstone has been considered correlative with the Early Jurassic Navajo sandstone by many workers, but it has been shown to be age-correlative with Middle Jurassic back-arc eolianites at some localities in the Mojave Desert, including the Cowhole Mountains (Busby-Spera, 1990).

The age of the Fairview Valley Formation is problematic. Miller (1978, 1981) interpreted it as a syn- to postorogenic deposit related to Permo-Triassic shortening and plutonism in the region. Walker (1987) assigned an Early Triassic age to the formation on the basis of an Early Triassic conodont assemblage recovered from one limestone bed, a mixed Permian and Early Triassic conodont assemblage from a second bed, and by lithologic correlation with units farther east in the Mojave Desert. However, preliminary ~170 Ma U-Pb zircon ages from the base of the Sidewinder section (Graubard and others, 1988; Mattinson, Schermer, and Busby, unpub. data) and recognition of a transitional

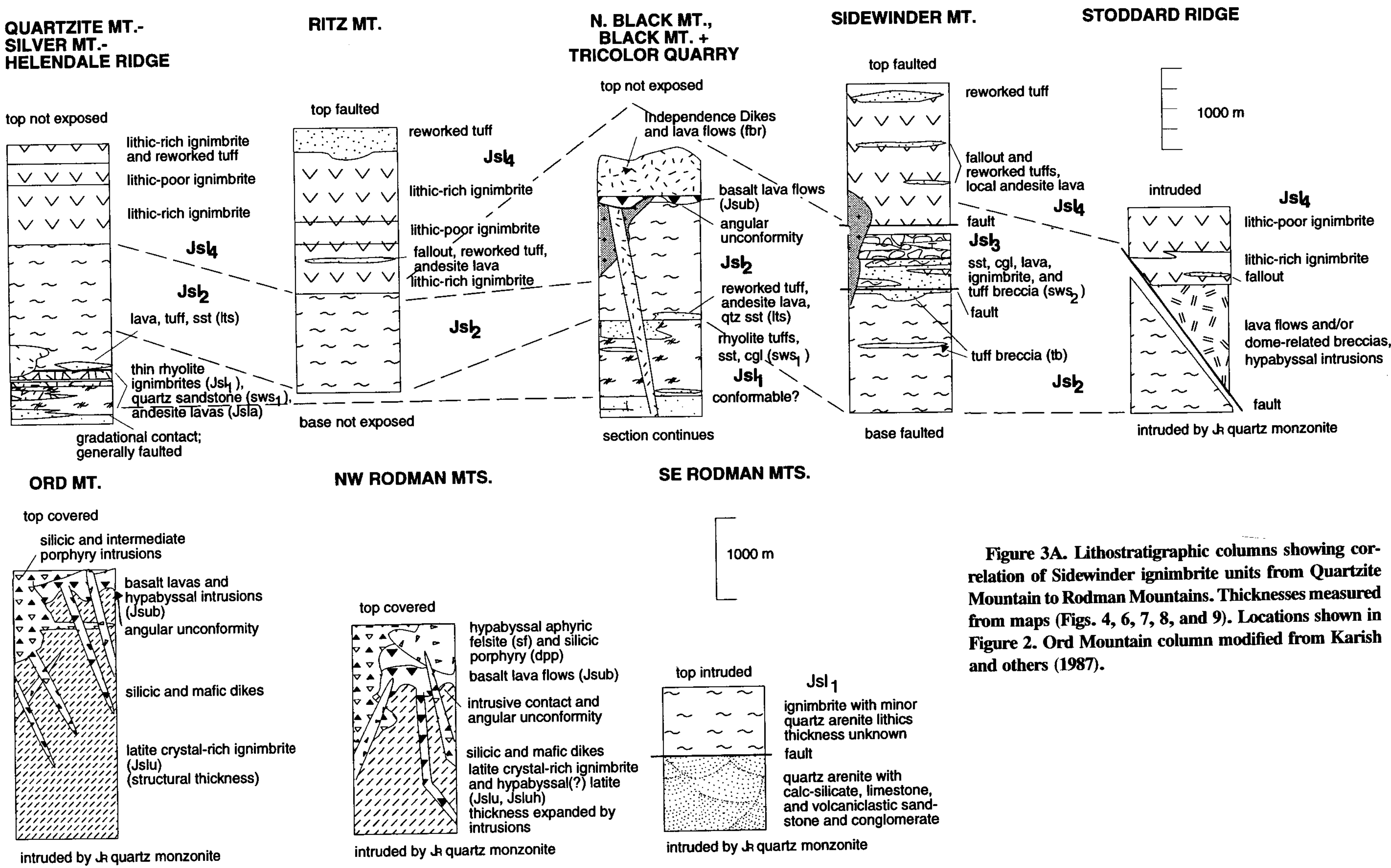



**Figure 3A. Lithostratigraphic columns showing correlation of Sidewinder ignimbrite units from Quartzite Mountain to Rodman Mountains. Thicknesses measured from maps (Figs. 4, 6, 7, 8, and 9). Locations shown in Figure 2. Ord Mountain column modified from Karish and others (1987).**

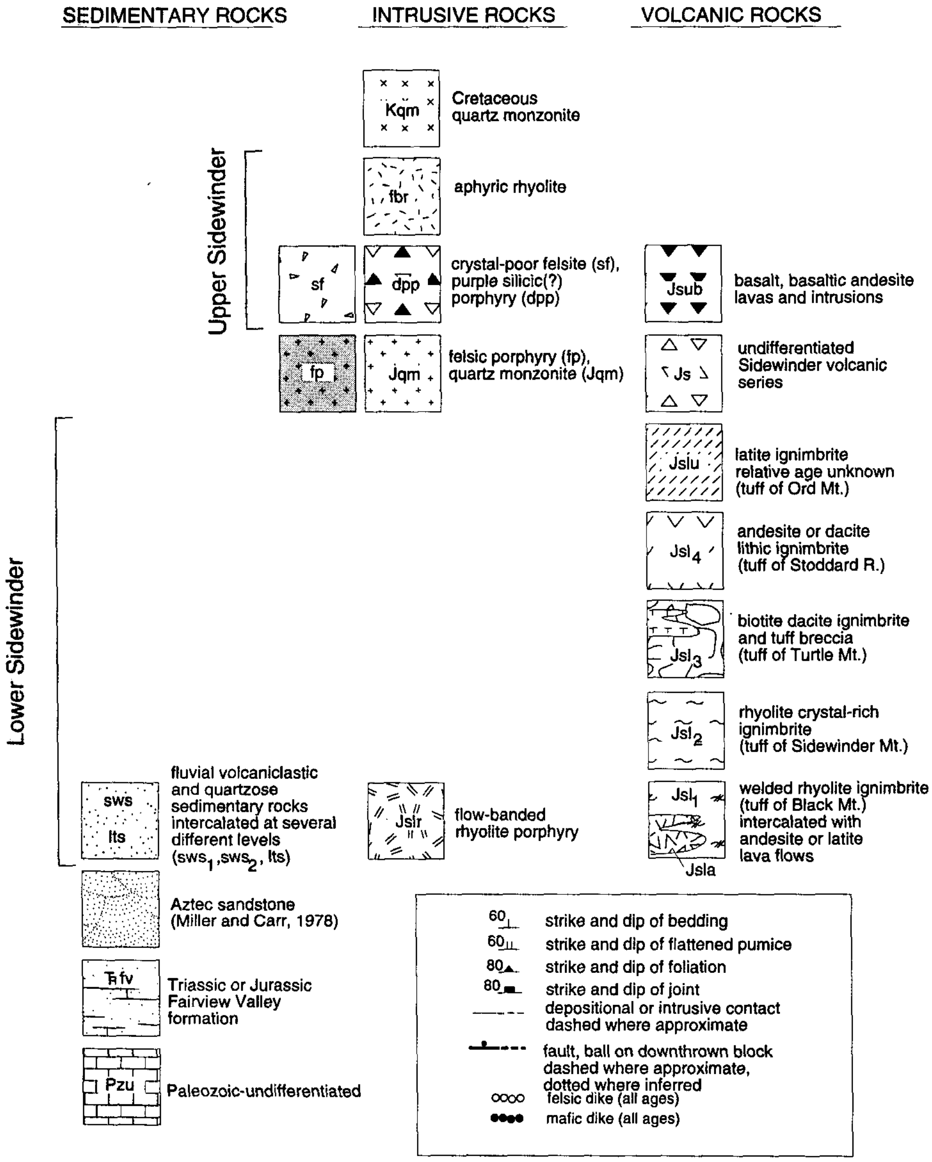



**Figure 3B. Explanation of symbols for columns in 3A and Figures 4, 6, 7, 8, and 9. For descriptions of units, see Table 1.**

unit between the basal Sidewinder section and the underlying Fairview Valley Formation suggest that the top of the Fairview Valley Formation may be Middle Jurassic. This would imply that the conodonts are reworked and therefore provide only a maximum age.

Regardless of the age of the Fairview Valley Formation, it is evident from the gradational upper contact that volcanism began prior to the end of shallow marine deposition. Although Sidewinder volcanic rocks were deposited subaerially (see below), it seems likely that the area remained low-standing during volcanism because cratonally derived quartz sands continued to be an important component of the early intra-arc sediments. The presence of epiclastic polymict volcanic breccias and alluvial fan conglomerates with Paleozoic limestone clasts (Miller, 1978) suggests local relief due to volcanic and/or tectonic activity. It is uncertain whether this relief was due to Jurassic extension (Schermer, 1993) or Permo-Triassic shortening (Miller, 1978, 1981; Walker, 1987, 1988).

### Explosive Volcanism and Caldera Formation: Lower Sidewinder Volcanic Series

Lower Sidewinder volcanism is characterized by large-volume silicic to intermediate composition ignimbrites. The Lower Sidewinder sequence is best preserved in the Black Mountain–Sidewinder Mountain area, where it is nearly 5 km thick (Figs. 2 and 3). Major ignimbrite units can be correlated on the basis of field and petrographic similarity from Quartzite Mountain to Stoddard Ridge, a distance of >30 km along strike, and one ignimbrite can be correlated for >60 km along strike (Figs. 2 and 3).

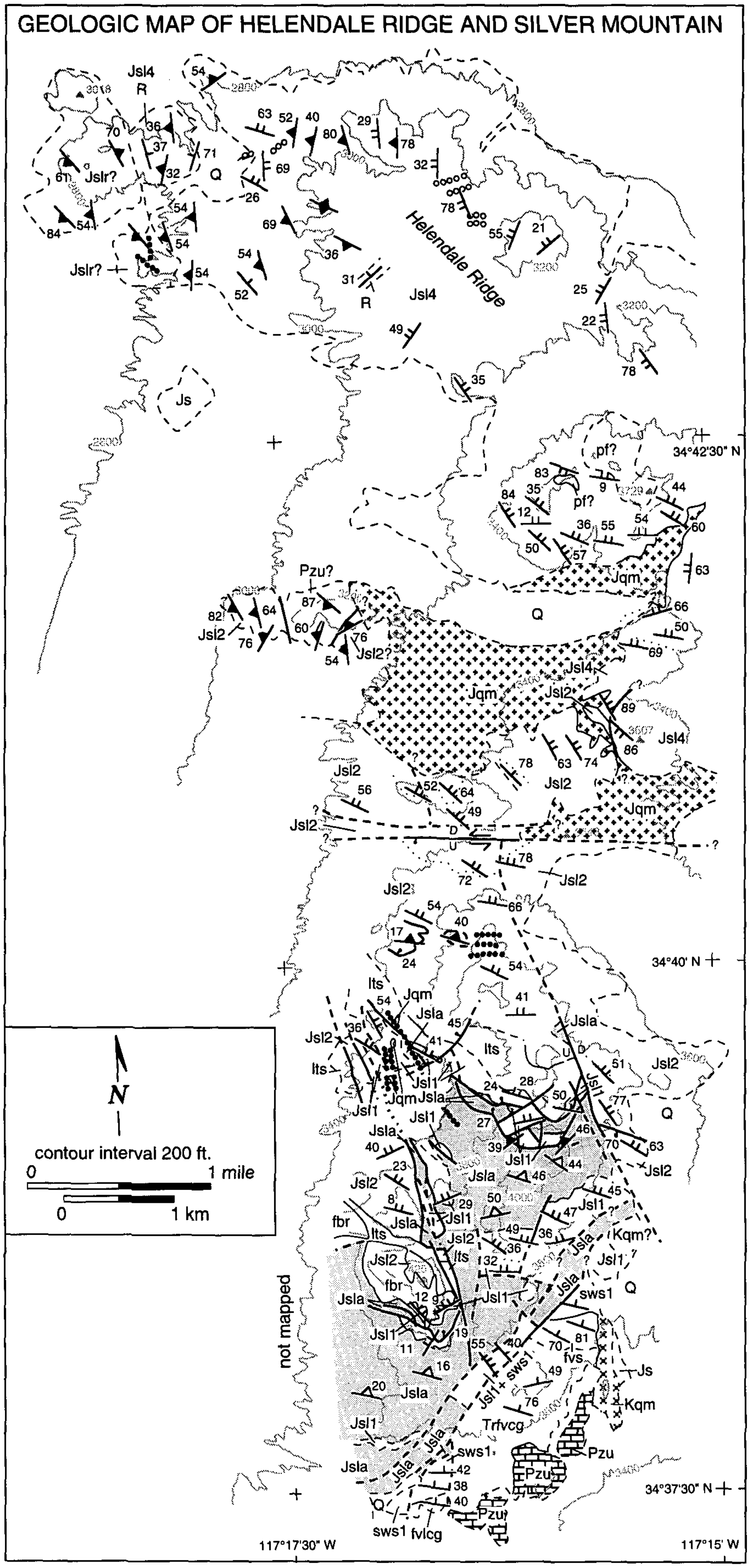
Lower Sidewinder volcanism includes the following phases (Table 1): *Phase 1*—emplacement of andesite lava flows and hypabyssal intrusions and contemporaneous eruption of rhyolite ignimbrite, followed by andesitic lava flows, silicic tuffs, and sedimentary rocks; *Phase 2*—caldera-forming eruption of rhyolite ignimbrite, followed by fluvial reworking and minor volcanism; *Phase 3*—caldera-forming eruption of biotite dacite ignimbrite and ongoing small-volume eruptions of rhyolite ignimbrite; and *Phase 4*—caldera-forming eruption of dacite ignimbrite and contemporaneous emplacement of a rhyolite dome. In addition, we follow Karish and others (1987) in assigning a welded latite ignimbrite in the eastern part of the study area to the Lower Sidewinder volcanic series, but its age relation to the rest of the Lower Sidewinder sequence remains uncertain.

**Phase 1: Andesite Lava Flows and Intrusions and Eruption of Tuff of Black Mountain Ignimbrite.** The earliest phase of Sidewinder volcanic eruptions reflects the transition from shallow-marine to terrestrial conditions and development of stratovolcanoes and a small caldera. Rocks included in this phase comprise crystal-rich andesite or latite lavas and hypabyssal intrusions (Jsla); crystal-poor rhyolite ignimbrite informally named the tuff of Black Mountain ($Jsl_1$); and crystal-poor andesite lavas, volcaniclastic sedimentary rocks, quartzose sandstone, and lithic lapilli tuff (lts; Figs. 1 and 2; Tables 1 and 2).

Phenocryst-rich andesite exposed only in the Silver Mountain region (Jsla; Table 1, Figs. 3 and 4) represents a vent-proximal lithofacies on the basis of the close association of lava flows and hypabyssal intrusions (Table 2, Fig. 3), although no vents have been discovered. Rhyolite ignimbrite ($Jsl_1$; Table 1) locally overlies flow-top breccias of the andesite lavas, but andesite hypabyssal intrusions also locally intrude other flow units of the ignimbrite, suggesting the two units are coeval (Figs. 3, 4, and 11).

The tuff of Black Mountain ($Jsl_1$) appears to have been erupted from a caldera, with both intra- and extracaldera facies preserved in the study area (Figs. 3 and 11). It is the oldest widespread volcanic unit (Table 2) and is distinguished by its pale green to white

**Figure 4. Geologic map of Quartzite Mountain–Silver Mountain–Helendale Ridge area (location in Fig. 2). Key to map units in Figure 3B and Table 1. Additional symbols: Trfvcg, fvlcg, fvs = polymict conglomerate, limestone cobble conglomerate, and sandstone, respectively, of Fairview Valley Formation. Andesite (Jsla) is shaded; undifferentiated Paleozoic (Pzu) is in brick pattern; Jurassic quartz monzonite (Jqm) is in cross pattern; other units unpatterned for clarity. None of the dikes indicated is known to be part of the Independence dike swarm. Simplified from mapping at 1:16,000 by E. R. Schermer (1988–1991).**




color and sparse phenocrysts relative to the other ignimbrites (Table 1, Fig. 5). The great thickness (>550 to ~800 m), massive nature, dense welding, and compositional homogeneity of the tuff at Black Mountain and Sidewinder Mountain (Tables 1 and 2; Figs. 3 and 5) suggest these are intracaldera accumulations, although flow units ~15 to >120 m thick are locally recognizable on the basis of variable lithic and pumice content. The reduced thickness (4–150 m) of the tuff in the Quartzite Mountain–Silver Mountain area, along with the thinness of individual flow units (2–15 m) and interstratification with quartzose sedimentary rocks and lavas, suggests that these are outflow equivalents. Thus, the western caldera margin must lie between Quartzite Mountain and Black Mountain (Fig. 10). Younger volcanism, faulting, and intrusion have resulted in incomplete preservation of the tuff of Black Mountain (preserved volume <1 km$^3$), however, and we have not recognized any caldera-margin faults or megabreccias associated with this ignimbrite.

The final stages of phase 1 volcanic activity are represented by complexly interfingering small-volume crystal-poor andesite(?) lava flows, lithic lapilli tuff and tuff breccia, volcaniclastic sedimentary rocks, quartzose sandstones, and minor ignimbrite (lts, Table 1; Figs. 4 and 7). These units are exposed locally between the tuff of Black Mountain and the tuff of Sidewinder Mountain ($Jsl_2$, see below; Table 2), and abrupt thickness and facies changes are apparent within and between each of the outcrop areas (Table 2; Figs. 4 and 7). Many angular clasts in the conglomerates and tuffs of this unit resemble the crystal-poor andesite lava flows; thus, these

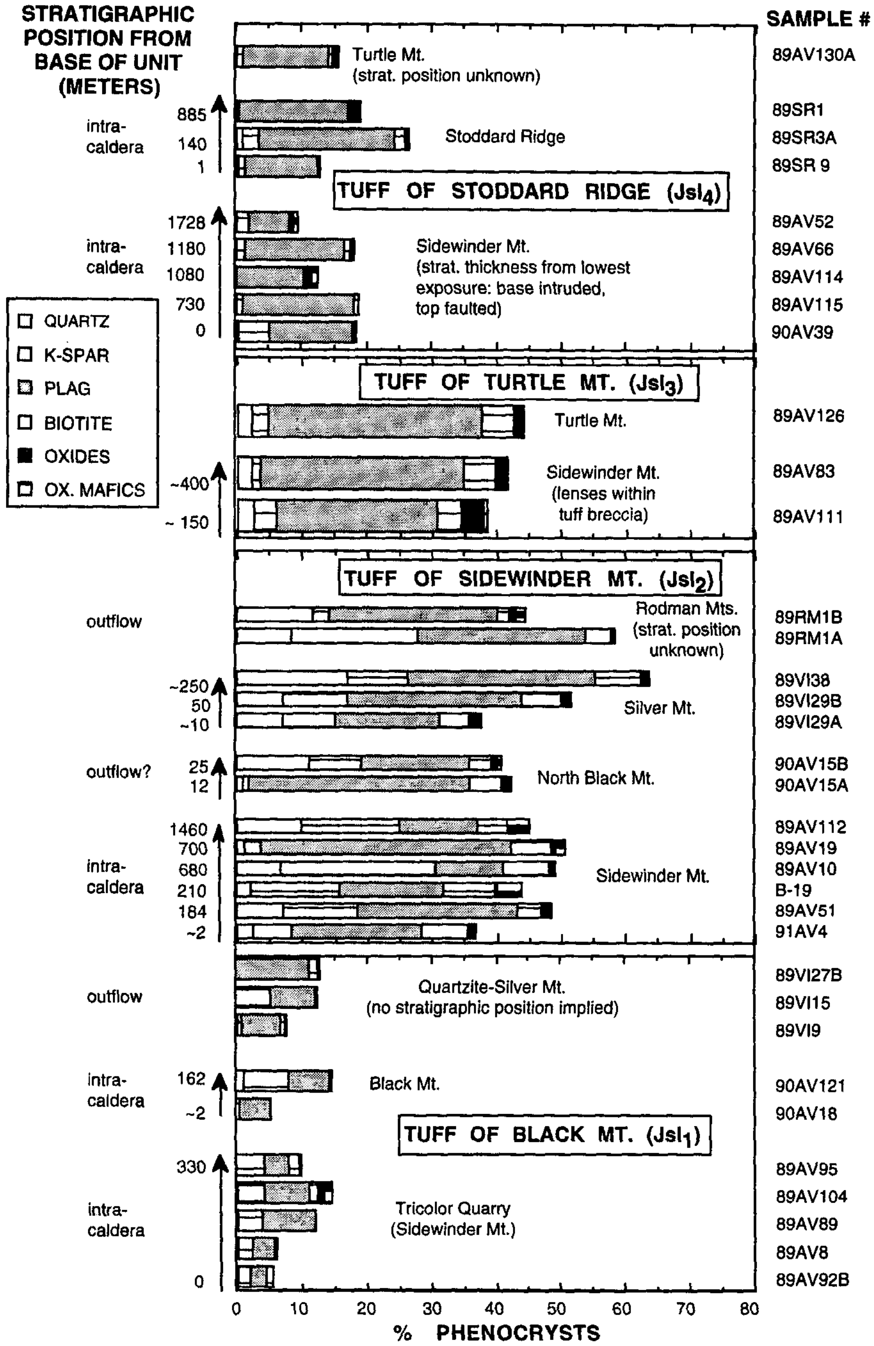



**Figure 5. Point count data from Lower Sidewinder ignimbrites, based on 1,000 points per thin section. Note that each ignimbrite unit has a distinctive phenocryst population. The tuff of Sidewinder Mountain is strongly and complexly zoned, with several interlayered dacite and rhyolite intervals, while the other ignimbrites are not strongly zoned. Ox. mafics = oxidized mafic minerals. Thicknesses are approximate and measured from maps. Upper sample of $Jsl_1$ at Black Mountain is extremely altered and may be reworked tuff.**

volcaniclastic rocks may record the eruption and collapse of small domes or distal facies of lava flows and their brecciated and reworked margins. Quartzose sandstones of unit lts overlying ignimbrite $Jsl_1$ at Black Mountain consist of reworked tuff and rounded monocrystalline quartz sand grains; although they contain a higher proportion of volcanic debris, the sandstones resemble those that underlie and are intercalated with the tuff of Black Mountain ($sws_1$, Table 1; Figs. 7 and 11).

Facies relationships between phase 1 volcanic and sedimentary rocks, as well as sedimentologic characteristics of the sedimentary rocks, provide clues to the paleogeography of the region at this time. The presence of quartzose sandstone with well-rounded quartz grains within the reworked tuff section at the top of the intracaldera sequence at Black Mountain (Figs. 3, 7, and 11) indicates that the cratonally derived quartz sand that was present during the late stages of Fairview Valley Formation deposition continued to gain access to intra-arc regions during phase 1 volcanic activity. The quartzose sandstones that are intercalated with the outflow facies ignimbrites at Quartzite Mountain show no preserved sedimentary structures other than planar lamination, so it is unclear whether they were deposited in shallow-marine or terrestrial environments. Neither the andesites nor the ignimbrites show evidence of interaction with either water or wet sediment, however, suggesting they were erupted and deposited subaerially. Postcollapse lavas and volcaniclastic rocks (lts) were deposited both outside of and within the Black Mountain tuff caldera.

**Phase 2: Caldera-forming Eruption of Tuff of Sidewinder Mountain Ignimbrite.** The second phase of volcanic activity in the west-central Mojave Desert is marked by the eruption of a large-volume rhyolite to dacite ignimbrite informally named the tuff of Sidewinder Mountain ($Jsl_2$). This ignimbrite is characterized by rare pumice and lithic fragments and abundant crystals, including coarse sanidine, highly embayed quartz, and biotite in variable proportions (Table 1, Fig. 5). The tuff of Sidewinder Mountain is widespread and volumetrically important; it maintains a thickness of >1,100 m across a region ~25 km from Silver Mountain to Stoddard Ridge and occurs in a thinner, fault-bounded sequence ~40 km farther east in the southeastern Rodman Mountains (Fig. 3, Table 2).

The tuff of Sidewinder Mountain is mineralogically zoned from base to top in both intra- and extracaldera sequences (Fig. 5). The base of the sequence consists of quartz-poor dacite conformably or locally unconformably deposited above phase 1 volcanic rocks (Fig. 3, Table 2). The basal dacite is overlain by quartz-rich rhyolite ignimbrite, and alternations of quartz-rich (rhyolitic) with quartz-poor (dacitic) ignimbrite occur throughout the section (Fig. 5, Table 2). The scale of this variation is on the order of 100–300 m, and there are three dacitic and three rhyolitic parts of

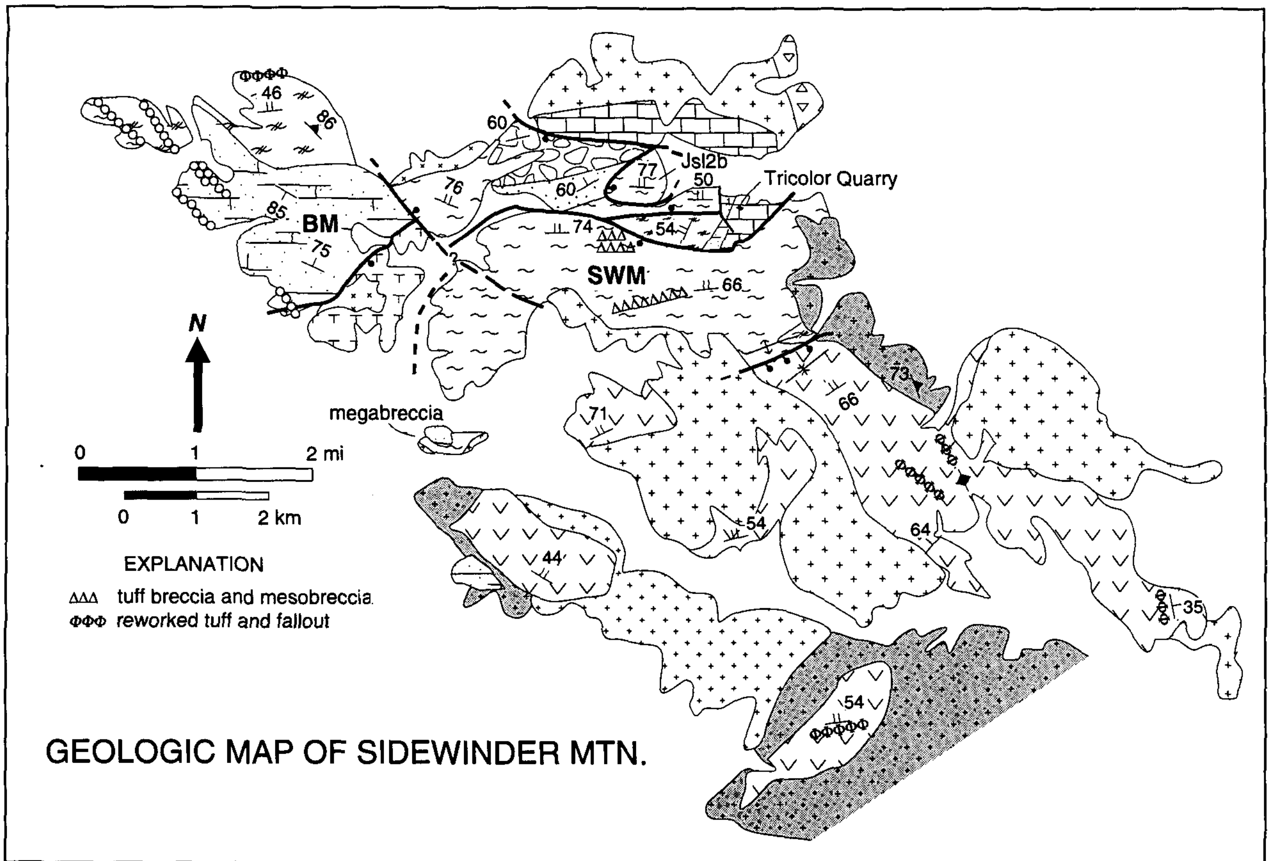



**Figure 6. Geologic map of Sidewinder Mountain region, simplified from mapping at 1:12,000 by E. R. Schermer (1988–1991). Location is shown in Figure 2; key to map units, in Figure 3B and Table 1. BM = Black Mountain (see Fig. 7 for more detail); SWM = Sidewinder Mountain. Note normal faults between tuff of Black Mountain ($Jsl_1$) and tuff of Sidewinder Mountain ($Jsl_2$) at Tricolor Quarry and between tuffs of Sidewinder Mountain and Stoddard Ridge ($Jsl_4$) at central Sidewinder Mountain. Megabreccia interpreted to result from caldera collapse occurs in western part of the figure.**

the sequence at Sidewinder Mountain (Fig. 5). Inasmuch as shards are only rarely preserved and pumice is sparse, we cannot determine whether the variations in composition are associated with simple, complex, or multiple cooling units. Faults and intrusions disrupt the thick zoned sections at Silver Mountain (Fig. 4), North Black Mountain (Fig. 7), Ritz Mountain (Fig. 8), and Stoddard Ridge (Fig. 9); thus, it is difficult to correlate specific dacitic or rhyolitic parts of the ignimbrite from one mountain to another.

*Intracaldera Facies.* Thick (average ~1,100 m; Fig. 3) sections of the tuff of Sidewinder Mountain occur at Silver Mountain (Fig. 4), Sidewinder Mountain (Fig. 6), Ritz Mountain (Fig. 8), and Stoddard Ridge (Fig. 9). The tuff in these regions exhibits limited variation in pumice and lithic lapilli abundance, although it is compositionally zoned (Tables 1 and 2). At Sidewinder Mountain, a 1,400-m-thick section of tuff of Sidewinder Mountain contains three intervals of tuff breccia that we interpret to be caldera-collapse meso- and megabreccias (Lipman, 1976; tb, Table 1; Figs. 3 and 6). A mesobreccia at the base of the tuff of Sidewinder Mountain contains clasts of the unconformably underlying tuff of Black Mountain (Table 2) in a matrix of dacitic tuff of Sidewinder Mountain. Two stratigraphically higher mesobreccias are composed of clasts of sparsely plagioclase-phyric silicic volcanic rocks as well as fragments of rhyolitic to dacitic Sidewinder Mountain tuff in a matrix of dacite tuff that appears in thin section to be nonwelded (Table 1). A fault block southwest of Sidewinder Mountain contains megabreccia composed of blocks of Fairview Valley Formation and possible Paleozoic limestone in a matrix of rhyolitic tuff of Sidewinder Mountain (Fig. 6). The blocks range from ~1 to 2 m, with one ~150 × 250 m block. The breccias probably record intermittent caldera collapse, particularly because they are associated with mineralogical changes in the tuff and contain clasts of older parts of the tuff in addition to clasts of older units. The clasts likely were derived from caldera walls or fault blocks within the caldera floor during episodic faulting that continued until late in the eruptive history of the caldera.

*Extracaldera Facies.* Possible outflow facies of the tuff of Sidewinder Mountain crop out in a fault block at northern Sidewinder Mountain ($Jsl_2b$, Fig. 6, Table 1). The section consists of ~600 m of crystal-rich rhyolite to dacite ignimbrite and tuff breccias that resemble the Sidewinder Mountain tuff except that they form relatively thin (1–15 m) flow units. Despite faulting that renders the stratigraphic relationship of this sequence to the thicker sequences uncertain, it appears to represent extracaldera facies based on the thinner flow units, multiple cooling units, and rapid verti-

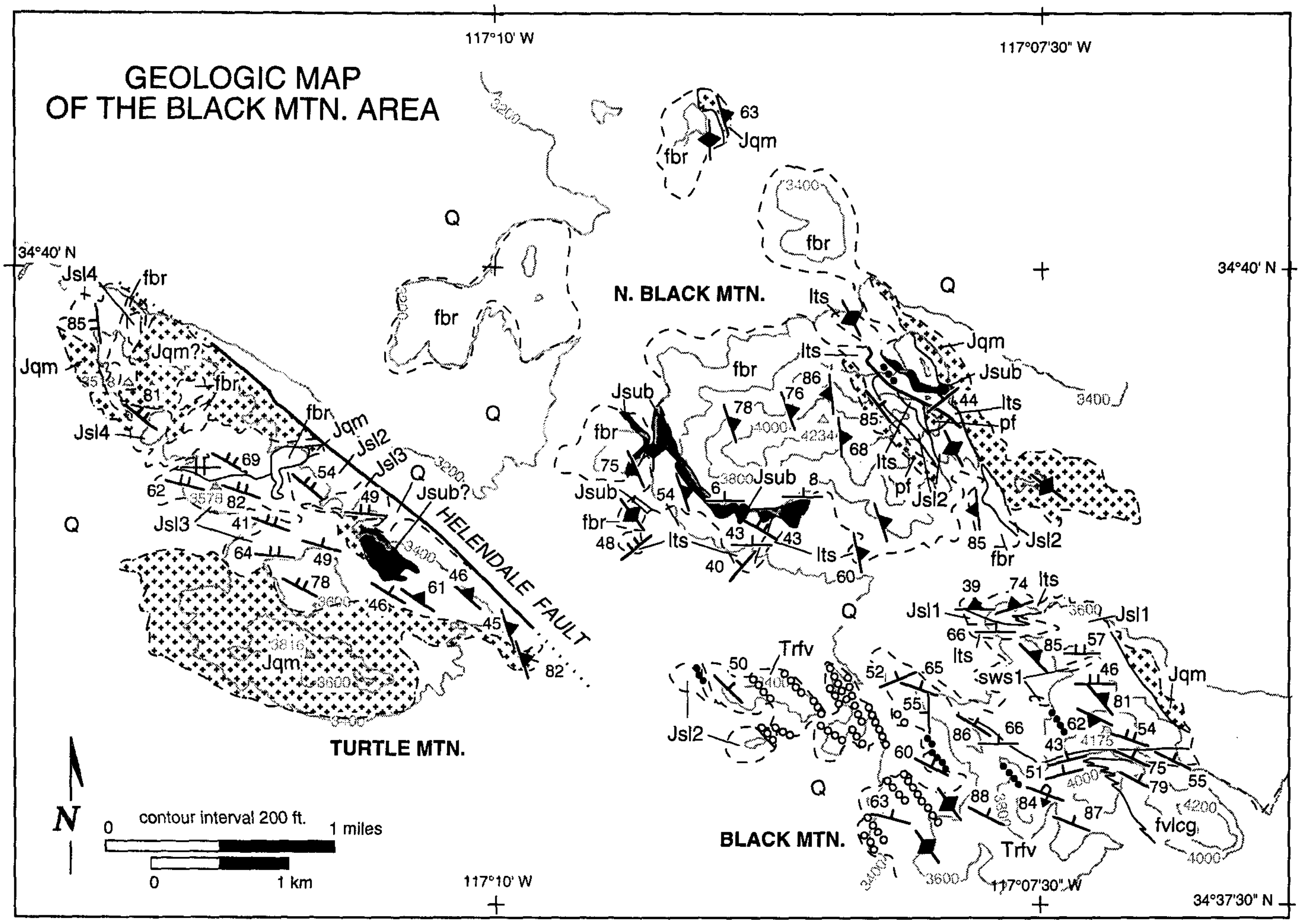



**Figure 7. Geologic map of the Black Mountain, North Black Mountain, and Turtle Mountain region (location shown in Fig. 2; key to map units, in Fig. 3B and Table 1; fvlcg = limestone cobble conglomerate of Fairview Valley Formation). Simplified from mapping at 1:16,000 by E. R. Schermer (1988–1990); Turtle Mountain and North Black Mountain are informal names. Attitudes and units within the Fairview Valley Formation and felsic dike locations are from Miller (1978); for clarity, not all felsic dikes are shown. Note (1) depositional contact between $Jsl_1$ and Trfv at Black Mountain; (2) angular unconformity juxtaposing gently dipping Upper Sidewinder (Jsub and fbr; Jsub is shaded for clarity) above granitic rocks (Jqm) and tilted Lower Sidewinder (lts) exposed at North Black Mountain; and (3) depositional contact between tuff of Turtle Mountain ($Jsl_3$) and tuff of Stoddard Ridge ($Jsl_4$) at Turtle Mountain; (4) northwest-striking dikes at Black Mountain are interpreted to be part of the Independence dike swarm based on age, trend, and composition.**

cal changes in mineralogy and lithic and pumice lapilli size and content (Table 1). The large pumice size and thickness of the tuff (Table 1) suggest that it was deposited proximal to the caldera.

Dacitic to rhyolitic ignimbrite that is mineralogically and texturally identical to the tuff of Sidewinder Mountain crops out in the southeastern Rodman Mountains, >40 km east of Sidewinder Mountain (Figs. 2, 3, and 5). The ignimbrite is in fault contact with eolian quartz arenite and calcareous siltstones interpreted as Aztec sandstone (Miller and Carr, 1978), but it contains sparse fragments of the sandstone, suggesting that the ignimbrite was deposited upon or erupted through lithified sandstone and siltstone. This relation and the fact that both the tuff and the Aztec sandstone are intruded by 166–171 Ma biotite quartz monzonite (Ar/Ar on hornblende; Karish and others, 1987) support correlation with the tuff of Sidewinder Mountain. Although the thickness of the Sidewinder Mountain tuff in the southeastern Rodman Mountains is unknown, owing to lack of bedding and sparsity of compacted pumice, the low degree of pumice compaction suggests the tuff is nonwelded or weakly welded, and thus thin relative to other exposures. The absence of this tuff in the region between Stoddard Ridge and the southeastern Rodman Mountains, its small preserved volume, its apparent absence of welding, and the lack of associated hypabyssal and volcanic rocks support the interpretation of this section as outflow facies.

*Caldera Margins.* It is difficult to locate the margins of the caldera that formed during the eruption of the tuff of Sidewinder Mountain, because probable structural margins have apparently been affected by postcaldera deformation and intrusion, and because outflow facies are poorly preserved. The most likely western margin of the caldera occurs at northwestern Silver Mountain, where strongly altered and sheared tuff of Sidewinder Mountain is faulted against strongly altered and brecciated siliceous

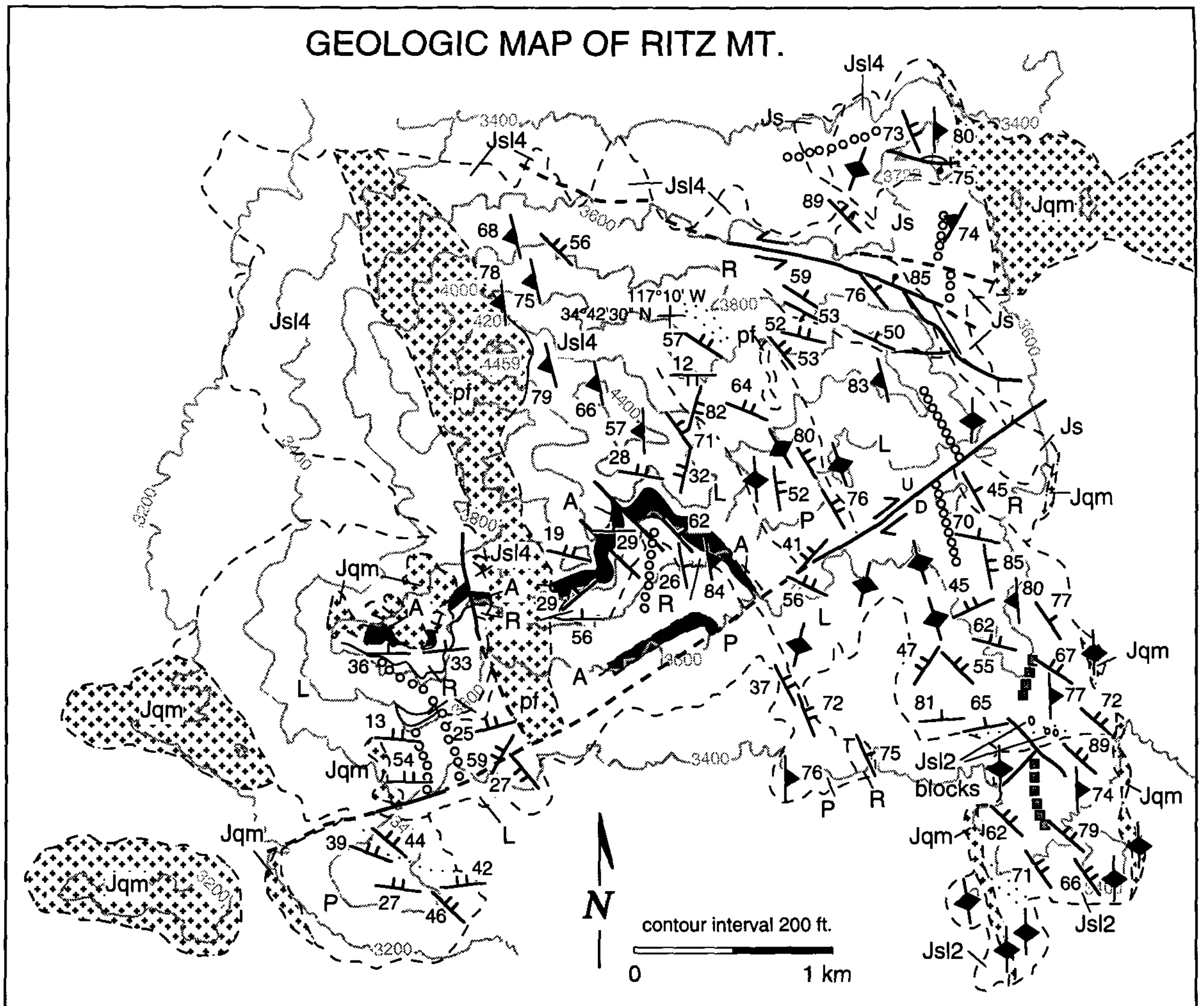



**Figure 8. Geologic map of Ritz Mountain (location shown in Fig. 2; key to map units, in Fig. 3B and Table 1). Simplified from mapping at 1:16,000 by E. R. Schermer (1990–1991). A = andesite lavas (shaded to outline large-scale folded structure); L = lithic lapilli-rich tuff; P = pumice lapilli-rich tuff; R = reworked tuff. Shaded squares indicate dacite porphyry dikes of unknown age. Felsic dikes are related to Jurassic plutons. Note blocks of $Jsl_2$ in $Jsl_4$ matrix adjacent to contact interpreted as caldera wall in southeast part of map.**

rock, which may be either recrystallized quartzose metasediments from the prevolcanic units or silicified igneous rock. Jurassic(?) quartz monzonite intrudes both the ignimbrite and the siliceous rock but is only slightly sheared (Figs. 4 and 10). The eastern margin of the caldera likely lies at or east of Stoddard Ridge (Fig. 10), which is the easternmost exposure of thick tuff of Sidewinder Mountain. At this locality, porphyritic intrusions (fp, Fig. 9) are intruded into sheared tuff; the tuff and porphyries are in turn intruded by undeformed Jurassic(?) quartz monzonite. The sheared tuff at Stoddard Ridge and Silver Mountain may reflect reactivation of caldera margin faults prior to emplacement of intrusions that exploited the faults as conduits. Owing to the absence of outflow facies of Lower Sidewinder ignimbrites beyond the postulated caldera margins (with the exception of southeast Rodman Mountains), however, it is possible the caldera was much larger than shown in Figure 10. The outcrop of megabreccia in Fairview Valley may represent part of the southern margin or floor of the Sidewinder Mountain tuff caldera.

The present-day extent of the caldera-filling tuff of Sidewinder Mountain is ~23 km from east to west. This distance represents a minimum caldera diameter, because although the area has been relatively unaffected by Tertiary normal faulting, it has been shortened by folding about northwest-trending axes (Schermer, 1993). Assuming that the caldera was roughly circular, that the east-west extent is the diameter, and that it contained an average thickness of 1,100 m of intracaldera ignimbrite, the volume of the preserved intracaldera tuff is estimated at ~450 $km^3$.

*Postcollapse(?) Fluvial Sedimentation and Minor Ignimbrite Eruptions.* A fault block at northern Sidewinder Mountain contains one of the rare preserved sedimentary sequences of Mesozoic age in the west-central Mojave Desert. The sequence consists of ~580 m of fluvially reworked tuff, volcanic lithic pebble conglomerate and sandstone, dacite lava flows and dome-related breccias and peperites, thin lithic tuff, and thin flows of rhyodacite-dacite crystal-rich ignimbrite and dacitic lithic lapilli ignimbrite ($sws_2$, Figs. 3 and 6; Tables 1 and 2). The lower part of the sequence contains abundant debris reworked from the tuff of Sidewinder Mountain, but the amount of material derived from other

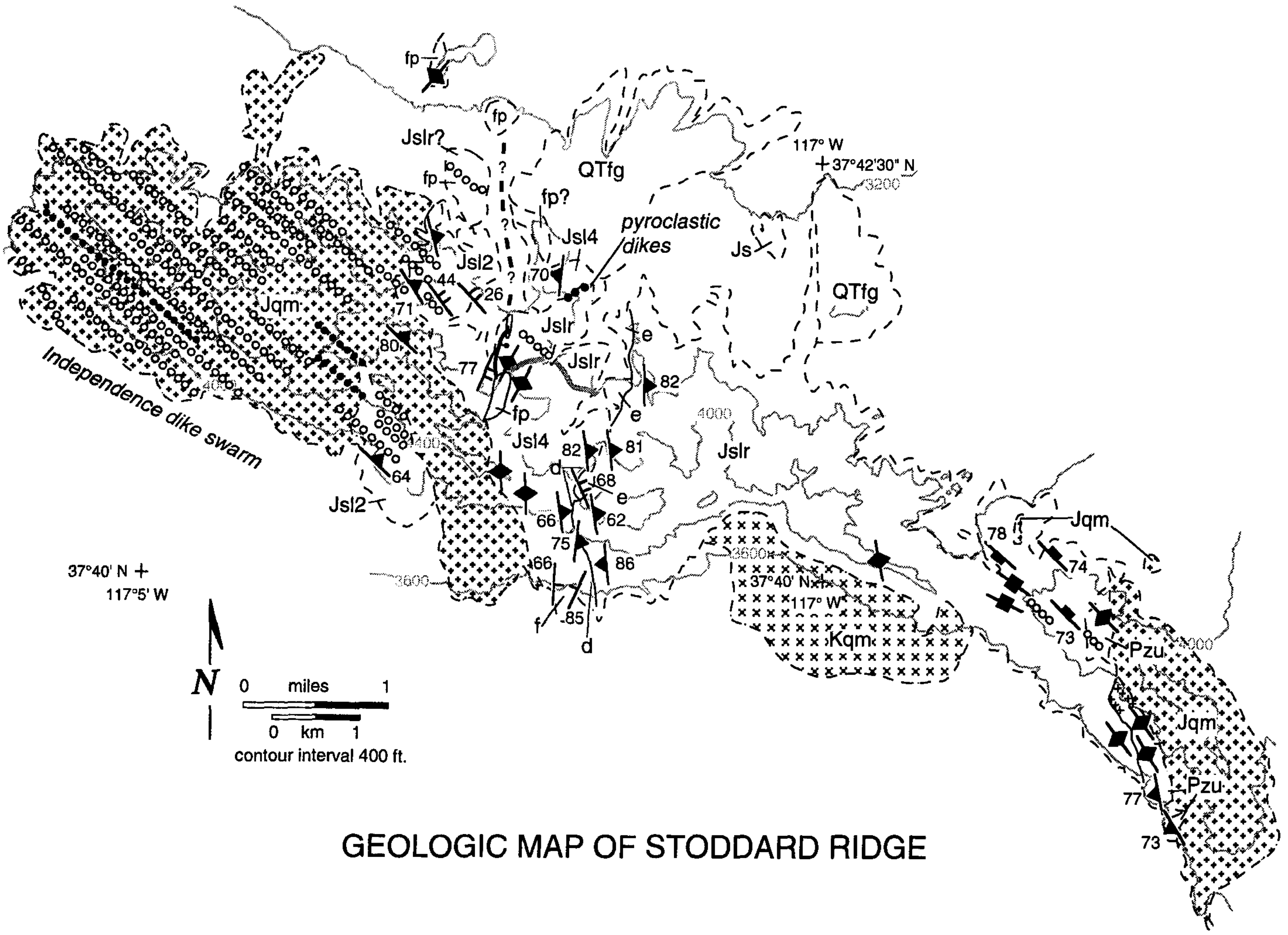



**Figure 9. Geologic map of Stoddard Ridge (location shown in Fig. 2; key to map units, in Fig. 3B and Table 1). Simplified from mapping at 1:24,000 by E. R. Schermer (1989–1990). Independence dike swarm generalized from Dibblee (1960c) and reconnaissance mapping; not all dikes are shown. Note that $Jsl_4$ depositionally overlies extrusive (e) facies of Jslr along contact marked by d but is also intruded by it along shaded part of contact. Pyroclastic dikes within intrusive part of Jslr are too small to be shown accurately but are shown schematically by shaded circles. f = fallout tuffs within $Jsl_4$.**

sources increases upsection. Sedimentary structures (Table 1) are interpreted to have formed by fluvial reworking of underlying tuffs and lavas as well as volcanic rock types that have not been recognized in the Sidewinder sequence. Overlying units include crystal-rich rhyodacitic to dacitic tuff that strongly resembles tuff of Sidewinder Mountain and dacitic lithic lapilli ignimbrite that contains a wide variety of volcanic lithic fragments (Table 2). The lithic lapilli ignimbrite does not resemble any other unit from the Lower Sidewinder volcanic series and crops out only at Sidewinder Mountain; thus, its source is likely outside the Sidewinder complex.

Although the postcollapse sedimentary sequence is in fault contact with intracaldera facies of the tuff of Sidewinder Mountain, the abundance of reworked tuff of Sidewinder Mountain suggests deposition after caldera formation, but possibly within the caldera during a lull in explosive volcanism. Peperitic contacts at the margins of dacite lavas suggest the presence of water, possibly in ephemeral streams or a caldera lake. Because of faulting, the original extent of the sedimentary and volcanic sequence above the tuff of Sidewinder Mountain is unknown; however, it appears to be restricted to Sidewinder Mountain (Table 2).

**Phase 3: Caldera-forming Eruption of Tuff of Turtle Mountain and Ongoing Small-Volume Eruptions of Tuff of Sidewinder Mountain.** The tuff of Turtle Mountain ($Jsl_3$, Table 1; Figs. 3, 5, 6, and 7) consists of ~600 m of gray crystal-rich biotite dacite lithic lapilli tuff, tuff breccia, and thin ignimbrite lenses in its eastern exposures at northern Sidewinder Mountain. To the west, the sequence is >790 m thick and consists predominantly of massive ignimbrite (Figs. 3 and 7; Table 2). The tuff breccia is monomict, composed entirely of ignimbrite clasts that are mineralogically and texturally similar to the matrix (Table 1). Clasts are subangular to subrounded and typically >25 cm in diameter. Crystal-rich tuff layers within the tuff breccia are massive to indistinctly bedded and graded.

The tuff breccia within the tuff of Turtle Mountain is interpreted as mesobreccia generated by caldera collapse (Fig. 11). The size and shape of clasts suggest they were transported some distance from their source area, and bedding in the crystal tuffs probably reflects redeposition of unconsolidated ash and crystals. Nevertheless, the tuff matrix ap-

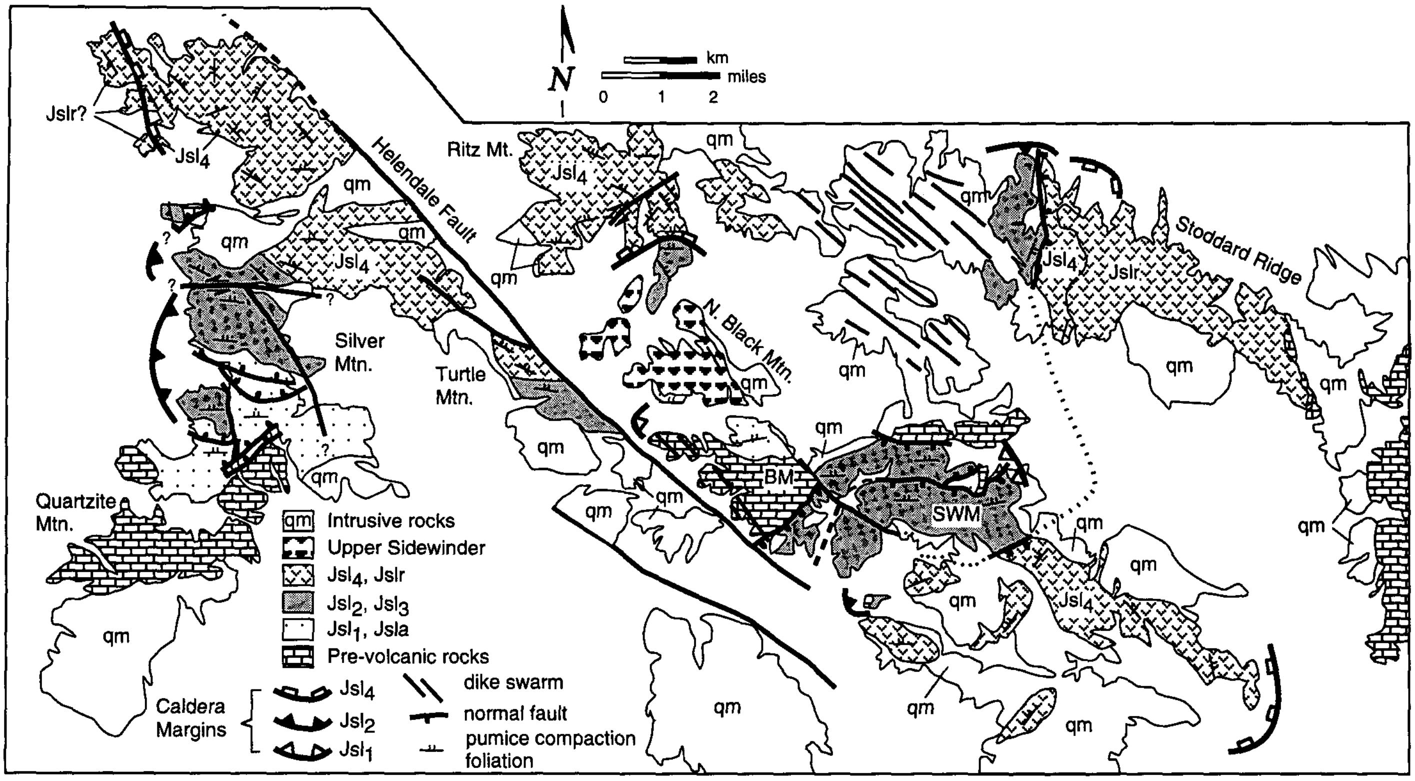



**Figure 10. Simplified map of the area from Quartzite Mountain–Helendale Ridge to Stoddard Ridge, showing major eruptive units, postulated caldera margins, and normal faults that have dismembered and tilted the caldera sections and are interpreted to be Middle to Late Jurassic in age. BM = Black Mountain; SWM = Sidewinder Mountain. See text for details.**

pears to have been uncontaminated by epiclastic debris, suggesting it represents a primary ignimbrite deposit. Cannibalization of early-erupted tuff of Turtle Mountain may have been accomplished during later phases of the ignimbrite eruption by disruption along a caldera margin fault. Mesobreccias of cannibalized ignimbrite within caldera-filling sequences also occur within the tuff of Sidewinder Mountain and have been recognized in other settings, including the English Lake District (Branney and Kokelaar, 1994).

The caldera associated with eruption of the tuff of Turtle Mountain appears to be nested within the Sidewinder Mountain caldera (Fig. 11). The mesobreccia is thickest at its eastern exposures, suggesting a caldera margin located east of the present exposures of Sidewinder Mountain. Owing to intrusions, however, it is unclear whether the tuff of Turtle Mountain also underlies Stoddard Ridge or whether the caldera boundary lies between Sidewinder Mountain and Stoddard Ridge. Interbedding of the tuff of Sidewinder Mountain with the tuff of Turtle Mountain and the broad petrographic similarity between dacitic parts of these tuffs (Fig. 5, Table 1) suggest that these two units may be genetically related, and perhaps were erupted from different parts of a zoned magma chamber.

The tuff of Turtle Mountain and underlying sedimentary rocks are missing from the sections at northern Silver Mountain and Ritz Mountain (Figs. 4 and 8), suggesting that a period of erosion followed eruption of the tuff of Turtle Mountain. Alternatively, the amount of caldera subsidence during eruption of the tuff of Sidewinder Mountain may have been variable, and greater subsidence at Sidewinder Mountain provided a local depocenter.

**Phase 4: Caldera-forming Eruption of Tuff of Stoddard Ridge and Contemporaneous Emplacement of a Rhyolite Dome.** The largest-volume eruption of the Lower Sidewinder series produced lithic and pumice lapilli dacite ignimbrite informally named the tuff of Stoddard Ridge ($Jsl_4$, Table 1; Figs. 3, 4, 6, 7, 8, and 9). The tuff is distinguished from other ignimbrites by its light gray rhyolite porphyry lithic fragments, dark brown matrix color, and constant plagioclase crystal content (~15%), although pumice and lithic concentrations vary with stratigraphic height (Tables 1 and 2; Figs. 3 and 5). The tuff of Stoddard Ridge is ≥1 km thick across the area from Helendale Ridge to Stoddard Ridge, and reaches >1,700-m thickness at Ritz Mountain and Sidewinder Mountain (Figs. 2 and 3). The great thickness and widespread nature of this ignimbrite suggest that it accumulated within a caldera (Fig. 11). No sections of the ignimbrite that could represent thinner outflow counterparts are recognized. The lateral variability and contact relations of the tuff of Stoddard Ridge with older units are complex (Table 2).

*Vertical and Lateral Variation of Intracaldera Facies.* The internal stratigraphy of the tuff of Stoddard Ridge suggests that it is composed of at least three eruptive units, which can be discerned where not obscured by tectonic foliation (for example, Helendale Ridge, Ritz Mountain; Table 2). The three units include a lower lithic lapilli ignimbrite (300–700 m thick), a middle pumice lapilli ignimbrite (~200–300 m thick), and an upper lithic lapilli ignimbrite (>700 m thick) (Table 2; Figs. 3 and 11). The tuff is largely moderately to densely welded, but variations in the aspect ratios of compacted pumice, local rheomorphic textures, and locally preserved incipiently welded shards suggest that several cooling units are present.

In addition to the multiple cooling units, several intercalated zones of fallout and fluvially reworked tuff, from ~1–10 m thick, within the thick ignimbrite at Sidewinder Mountain, Ritz Mountain, and Stoddard Ridge (Figs. 6, 8, and 9), suggest that eruption and collapse occurred in several stages. Hornblende andesite lavas are locally intercalated with the reworked tuffs that crop out approximately in the middle of the sequence at Ritz Mountain and southeastern Sidewinder Mountain (Table 2; Figs. 3 and 8).

The tuff of Stoddard Ridge was deposited upon several different units across the region and locally appears to overlie older units ($Jsl_2$, $Jsl_3$) with slight (<20°) angular unconformity (for example, Turtle Mountain, Fig. 7; Table 2). The base of the ignimbrite at northern Silver Mountain is a mesobreccia with blocks of tuff of Sidewinder Mountain from 0.3–3 m long. At Stoddard Ridge, the tuff was deposited directly on dome-related breccias and welded tuffs of a rhyolite porphyry dome complex (Jslr), and it contains abundant lithic fragments of that porphyry throughout (Table 1; Figs. 3, 9, and 11). The dome complex occurs as hypabyssal intrusions into prevolcanic rocks and exogenous and endogenous dome breccias. Tuff of Stoddard Ridge depositionally overlies extrusive parts of the dome complex, yet dikes, sills, and hypabyssal bodies that emanate from the complex intrude the tuff along the east flank of central Stoddard Ridge (Fig. 9), suggesting that portions of the rhyolite porphyry are coeval with and postdate the eruption of the tuff. These age and spatial relationships suggest the dome complex is a result of late ring-fracture magmatism in the Stoddard Ridge caldera (Fig. 11).

*Caldera Margins.* The eastern and western limits of thick sections of the tuff of Stoddard Ridge appear to coincide approximately with those for the tuff of Sidewinder Mountain. It is unclear if this is a result of later normal faulting (Fig. 10; see below), or if the caldera margins were coincident. The porphyry dome complex (Jslr) at Stoddard Ridge coincides with the eastern limit of exposures of Stoddard Ridge tuff. In this area, hypabyssal intrusions of several ages and composition, dikes, and pyroclastic dikes intrude along a north-south fault zone. Although no megabreccia is present, it is possible that eastern Stoddard Ridge represents a dome complex along a part of a ring fracture zone (Figs. 10 and 11), with the pyroclastic intrusions representing an exhumed vent (for example, Reedman and others, 1987). The westernmost exposures of the tuff of Stoddard Ridge occur at northwestern Helendale Ridge, where hypabyssal rocks appear to intrude the tuff, although both units are sheared (Fig. 4). Exposure is too poor to determine whether the northwest-striking shear fabric is cut by Jurassic or Cretaceous quartz monzonites (too small to show in Fig. 4); thus it is unclear whether the shearing is due to reactivation of caldera-margin faults or a younger unrelated fault zone.

A small portion of a caldera margin of the Stoddard Ridge tuff may be preserved at southeastern Ritz Mountain (Figs. 8 and 10). Here, the middle part of the sequence contains blocks of as much as 3 m of tuff of Sidewinder Mountain in a matrix of tuff of Stoddard Ridge, which strikes into a steep contact with the tuff of Sidewinder Mountain (Fig. 8, Table 2). This exposure supports our interpretation that caldera collapse occurred in several stages inasmuch as the megabreccia formed after accumulation of >800 m of the lower part of the ignimbrite sequence.

The caldera of the tuff of Stoddard Ridge is ~25 km in diameter based on restoring 10–15 km of dextral slip on the Helendale fault (Garfunkel, 1974) and ~15% extension on east-striking normal faults (Schermer, 1993). Given that no Tertiary extension has been recognized to have formed the valleys between these ranges, assuming passive intrusion of plutons (Fig. 2), and not restoring Cretaceous folding (Schermer, 1993), this is a rough estimate of the minimum caldera size. If we assume a roughly circular caldera with an average tuff thickness of 1,700 m (Fig. 3), the volume of the tuff of Stoddard Ridge is ~800 $km^3$. If the ~5-km width of plutons is subtracted, the volume is ~530 $km^3$.

*Postcollapse Reworking.* The top of the Stoddard Ridge tuff passes gradationally upward into a 300-m-thick section that records reworking of mainly the tuff of Stoddard Ridge on debris aprons and by ephemeral streams (Fig. 11). The lower part of this section is predominantly crudely stratified tuff breccias supported in a matrix of nonsorted tuff with rare pumice (Table 1); these are interpreted to be the deposits of debris flows generated by remobilization of the tuff of Stoddard Ridge, although some could be primary ignimbrites. The debris flow deposits are intercalated with discontinuous lenses of tuffaceous siltstone, sandstone, and pebbly sandstone that increase in abundance and lateral continuity upsection (Table 1). The sandstones are poorly sorted, medium to coarse grained, plane bedded to massive, and notably lack cross-stratification, similar to the hyperconcentrated flood-flow–deposited sandstones of Smith (1987). These are the product of high-concentration, turbulent dispersions intermediate between dilute stream flow and viscous debris flow.

The postcollapse section at the top of the tuff of Stoddard Ridge appears to record "volcanism-induced aggradation" (Smith, 1987), where eruption-produced sediment supply chokes streams to produce debris flows and hyperconcentrated flood flows. In this scenario, initial deposition occurs from debris flows, whose deposits are then partially reworked by braided streams. The finer-grained nature of the upper part of the section probably reflects diminished sediment supply as volcanism approached quiescence, although the presence of thin ignimbrites(?), not easily distinguished from debris flow deposits, suggest minor ongoing volcanism (Fig. 11).

**Caldera-forming Eruption of Tuff of Ord Mountain.** A fifth major eruptive unit of Lower Sidewinder volcanic series, termed here the tuff of Ord Mountain (Jslu), is exposed at Ord Mountain and the northwestern Rodman Mountains (Figs. 2 and 3), but because this unit is not in contact with other Lower Sidewinder volcanic rocks, its relative age is uncertain. The tuff of Ord Mountain consists of a thick monotonous sequence of welded latite ignimbrite (Karish, 1983). The latite ignimbrite at Ord Mountain has a structural thickness of >4 km (Fig. 3, Table 1); however, the stratigraphic thickness is unknown due to faulting and poor preservation of pumice compaction foliation (Karish, 1983; Karish and others, 1987). The ignimbrite is intruded by Middle Jurassic quartz monzonite and unconformably overlain by basaltic andesite lavas of the Upper Sidewinder volcanic series. The same latite occurs in the northwestern Rodman Mountains, where it occurs as locally pumice-rich (as much as 20%), densely to weakly welded ignimbrites, and as hypabyssal intrusive rocks with similar petrographic and field characteristics to the ignimbrite (Table 1, Fig. 3). The latite ignimbrite in the Rodman Mountains is >1 km thick, locally has a thin (<2–3 m) sequence of reworked tuff conformably above it, and is tilted and overlain unconformably by a thin clastic sedimentary sequence and basaltic andesite lavas of the Upper Sidewinder volcanic series (Schermer, 1993).

Because of the great apparent thickness and massive, generally welded nature of the latite ignimbrite of Ord Mountain, it is likely the tuff represents an intracaldera accumulation. Younger intrusions have obliterated any

TABLE 2. SUMMARY OF CONTACT RELATIONS AND LATERAL VARIABILITY OF LOWER SIDEWINDER VOLCANIC ROCKS

| Area/ Unit | Quartzite Mt., Silver Mt., Helendale Ridge | Turtle Mt. | Ritz Mt. | Black Mt., N Black Mt. | Sidewinder Mt. | Stoddard Ridge | Ord Mt. (Karish and others, 1987) | NW Rodman SE Rodman Mts. |
|---|---|---|---|---|---|---|---|---|
| Jslu* | | | | | | | 4 km structural thickness; welded throughout rare lithics, pumice to 7%; top ang. unconfm with upper SWV, base n.e. or intruded | NWRM: >1 km thick in two fault blocks; rare lithics; pumice to 20%; dense to moderate welding top, base as at Ord Mt. |
| $Jsl_4$ | >990 m thick[†] base is mesobrx[§] with $Jsl_3$ clasts; top faulted, intruded. Internal strat.: >100 m lithic-rich top? with r.w. tuffs 290 m pumice-rich 700 m lithic-rich | Thickness, attitude uncertain due to pervasive intrusions but >340 m; mostly lithic-rich | >1,730 m; base n.e., top confm. with r.w. tuffs; tuffs faulted at top Internal strat.: 289 m r.w. tuff 850 m lithic-rich 287 pumice rich, locally rheoig. and mesobrx 183 m lithic rich 97 m andesite lava + r.w. tuff >320 m lithic-rich | | >1,750 m base intruded, top faulted Internal strat. uncertain due to deformation: >300 m r.w. tuffs at highest exposed level; ~200 m andesite lava, r.w. tuffs in middle to upper parts | >860 m thick; top faulted >500 m pumice-rich ~360 m lithic-rich with fallout, r.w. tuffs ~140 m above base | | |
| Jslr | | | | | | >4.5 km thick mostly intrusive facies base intrudes Precambrian? gneiss, schist; top overlain by $Jsl_4$ but intrudes $Jsl_4$ locally Internal strat.: ~200 m thick silicic ig. locally as inclusion at top; also dikes, sills, pyroclastic dikes >500 m exogenous dome, dome brx at top ~4,000 m intrusive brx, massive, hypabyssal | | |
| $Jsl_3$ | | >790 m thick, base intruded, top slight ang. unconfm. with $Jsl_4$, ~2 m r.w. tuffs at contact; mostly massive ig. with up to 15% pumice | | BM: thickness unknown (intruded) mostly massive ig., some tuff brx | ~600 m thick top intruded mostly tuff brx, rare massive ig. | | | |
| $sws_2$ | | | | | 580 m thick; top confm with $Jsl_3$ Internal strat.: 100 m dacite lithic lapilli ign. 10–60 m $Jsl_2$ 320 m sed rocks and dacite lavas, dome brx 100 m $Jsl_2$, r.w. $Jsl_2$. | | | |
| $Jsl_2$, $Jsl_{2b}$ | >1,300 m confm over lts with faulted top; ~1,900 m? in block with faulted bottom and confm top with $Jsl_4$ Internal strat.: >300 m dacite + rhy ~800 m rhyolite ~200 m dacite | Lens or block in $Jsl_3$, ~200 m thick, contacts with $Jsl_3$ n.e. | >1,100 m thick, base faulted, top unconfm with $Jsl_4$: mesobrx clasts of $Jsl_2$ in $Jsl_4$ matrix and bedding, pumice foliation parallel in $Jsl_2$, $Jsl_4$, but at high angles to contact. Internal strat.: dacite, rhyolite interstratified on 20–200 m scale | >50 m thick, faulted top Internal strat.: >40 m rhyolite ~10 m dacite | $Jsl_2$: 1,400 m thick, complexly zoned; top confm with $sws_2$ Internal strat.: ~600 m complexly zoned with 0–360 m dacitic tuff brx with $Jsl_2$ clasts at top ~100 m rhyolite ~80 m dacite 0–50 m dacitic tuff brx, $Jsl_2$ clasts ~410 m rhyolite ~200 m dacite with $Jsl_1$ tuff breccia at base $Jsl_{2b}$: ~600 m thick, fault bounded, with flow units 1–15 m thick | Faulted, intruded sequence; thickness estimated at 1,400 m Internal strat. unknown, includes dacite + rhyolite | | SERM only: pumice foliation not developed; contacts faulted and intruded, thickness unknown. Internal strat. unknown, includes dacite + rhyolite sparse lithics of quartzite, calcareous siltst. |
| lts | 20–200 m thick; mostly xl-poor andesite 0–190 m thick, but flow thickness unknown. Lithic tuffs with andesite clasts; rare seds. Top confm with $Jsl_2$, locally faulted | | | NBM: >80 m thick; mostly lithic lapilli and crystal tuffs, densely welded rhy. ig., volcanogenic seds; complexly interfingered, with one ~10 m thick xl-poor andesite flow at top of sequence; top confm with $Jsl_2$, base covered. BM: >50 m thick; mostly densely welded rhy. ig., r.w. tuffs are qtz-rich; top probably at NBM, but intervening area n.e. | | | | |

TABLE 2. (*Continued*)

| Area/ Unit | Quartzite Mt., Silver Mt., Helendale Ridge | Turtle Mt. | Ritz Mt. | Black Mt., N Black Mt. | Sidewinder Mt. | Stoddard Ridge | Ord Mt. (Karish and others, 1987) | NW Rodman SE Rodman Mts. |
|---|---|---|---|---|---|---|---|---|
| $Jsl_1$ | 4 m–>150 m thick; flow units 2–15 m thick; base gradational with top of FV, locally faulted. Typically overlain confm. by lts; locally top may be intruded by or overlain by Jsla (n.e.) | | | 840 m thick; base confm. on FV, locally faulted, top confm. with lts. dense to mod welding in lower 660 m upper ~150 m contains qtz sst, r.w. tuff, rhyolite ig. | Tricolor Quarry: ~500 m thick; base confm. on FV, top faulted entire section possibly densely welded (shards variably preserved); flow units ~15–120 m thick discernible Central SWM: ~150 m thick; base faulted, top confm with $Jsl_2$: shallow contact, marked by mesobrx of $Jsl_1$ clasts in $Jsl_2$ matrix, but steep dips (45–65) in pumice foliation above and below | | | |
| Jsla | ~100 m thick lavas, intrusions; flow thickness unknown; lower contacts with FV faulted or n.e.; confm overlain by $Jsl_1$ | | | | | | | |

*See Figure 3 and Table 1 for unit descriptions.
†Thicknesses measured from maps; internal stratigraphy listed top to bottom.
§Abbreviations: ang. unconfm. = angular unconformity; brx = breccia; confm = conformable; FV = Fairview Valley Formation; ig. = ignimbrite; n.e. = not exposed; r.w. = reworked; seds = sedimentary rocks; strat. = stratigraphy; BM = Black Mt.; NBM = North Black Mt.; RM = Rodman Mts.

caldera-bounding structures, but no latite tuff occurs west of Ord Mountain or east of the Rodman Mountains. Moreover, there are no places where ignimbrites of the Sidewinder Mountain–Stoddard Ridge region and the Ord Mountain tuff are in contact, suggesting that the sequences are different in age and/or that they were confined to separate basins.

**Summary and Discussion of Lower Sidewinder Volcanic Series.** *Caldera-forming Eruptions.* Volcanism during Lower Sidewinder time was dominated by moderate to large-volume caldera-forming eruptions (Fig. 11). The earliest volcanic and sedimentary rocks (phase 1) record the transition from shallow-marine sedimentation to subaerial volcanism. Volcanic activity during this phase included formation of small-volume, low-relief stratocones and a small(?) rhyolite caldera. Cratonally derived quartz sand gained access to the arc region before and during phase 1 eruptions. A succession of three large-volume caldera-forming ignimbrite eruptions followed (phases 2, 3, and 4), interrupted locally (and/or intermittently) by periods of reworking of pyroclastic debris.

Jurassic volcanic rocks in the west-central Mojave desert are best preserved in the intracaldera regions between Silver Mountain and Stoddard Ridge, and in the Ord and Rodman Mountains. No ignimbrite units are known to the west of the proposed western caldera margins (for example, Shadow Mountains; Fig. 1). The nearest units mapped as "Mesozoic volcanic rocks" occur ~20 km to the northwest in the Kramer Hills, where they are altered felsic intrusive rocks (Dibblee, 1960a; Schermer, unpub. data) and ~10 km to the north in the Iron Mountains (Fig. 1), where the Hodge Volcanic series (Bowen, 1954), with a minimum age of 164 Ma (U-Pb zircon), is strongly deformed and intruded by 148 Ma undeformed plutons (Boettcher, 1990; Boettcher and Walker, 1990, 1993). The Hodge Volcanic rocks in this area resemble the tuff of Sidewinder Mountain in thin section; however, the extreme deformation and sparsity of geochronologic data renders estimation of its stratigraphic position relative to Sidewinder volcanic series uncertain.

That the Lower Sidewinder ignimbrites were erupted over a short time span is suggested by the regional and local-scale conformity between successive ignimbrite sequences (Fig. 11). Sedimentary sequences that might reflect inter-eruption hiatuses are rare, and where present, are intercalated with ignimbrites related to the underlying caldera-forming ignimbrite. This interpretation is also supported by U-Pb zircon data (Mattinson, Schermer, and Busby, unpub. data) that suggest the time span of eruption of Lower Sidewinder ignimbrites is <5 m.y.

*Accumulation and Preservation of Sedimentary Sequences.* Sedimentary rocks are rare throughout the Sidewinder volcanic sequence, and they appear to be restricted to intracaldera sections. We attribute this distribution to a lack of basins outside of the areas of caldera subsidence. The ubiquitous interstratification of primary volcanic rocks with the sedimentary successions suggests there were no long lulls in volcanism; this may explain why sedimentary rocks are so sparsely represented.

**Postcaldera Normal Faulting, Plutonism, and Erosion**

Following Lower Sidewinder explosive volcanism, there was a period of tilting and normal faulting (Fig. 12) associated with a north-south extensional event described in detail in Schermer (1993). East-striking normal faults resulted in northward tilting of ignimbrites in the western part of the study area (Figs. 4, 6, 9, and 10; Schermer and Busby-Spera, 1989; Schermer, 1993), and Karish (1983, p. 43) speculated that an episode of tilting at Ord Mountain may be related to Middle Jurassic normal faults. Jurassic(?) quartz-monzonite porphyry intrudes normal faults at Sidewinder Mountain, Black Mountain, and possibly at Stoddard Ridge and Quartzite Mountain–Silver Mountain (Figs. 4, 6, 9, 10, and 12).

The Jurassic(?) plutons (Jqm, Table 1) are generally undeformed, porphyritic, and het-

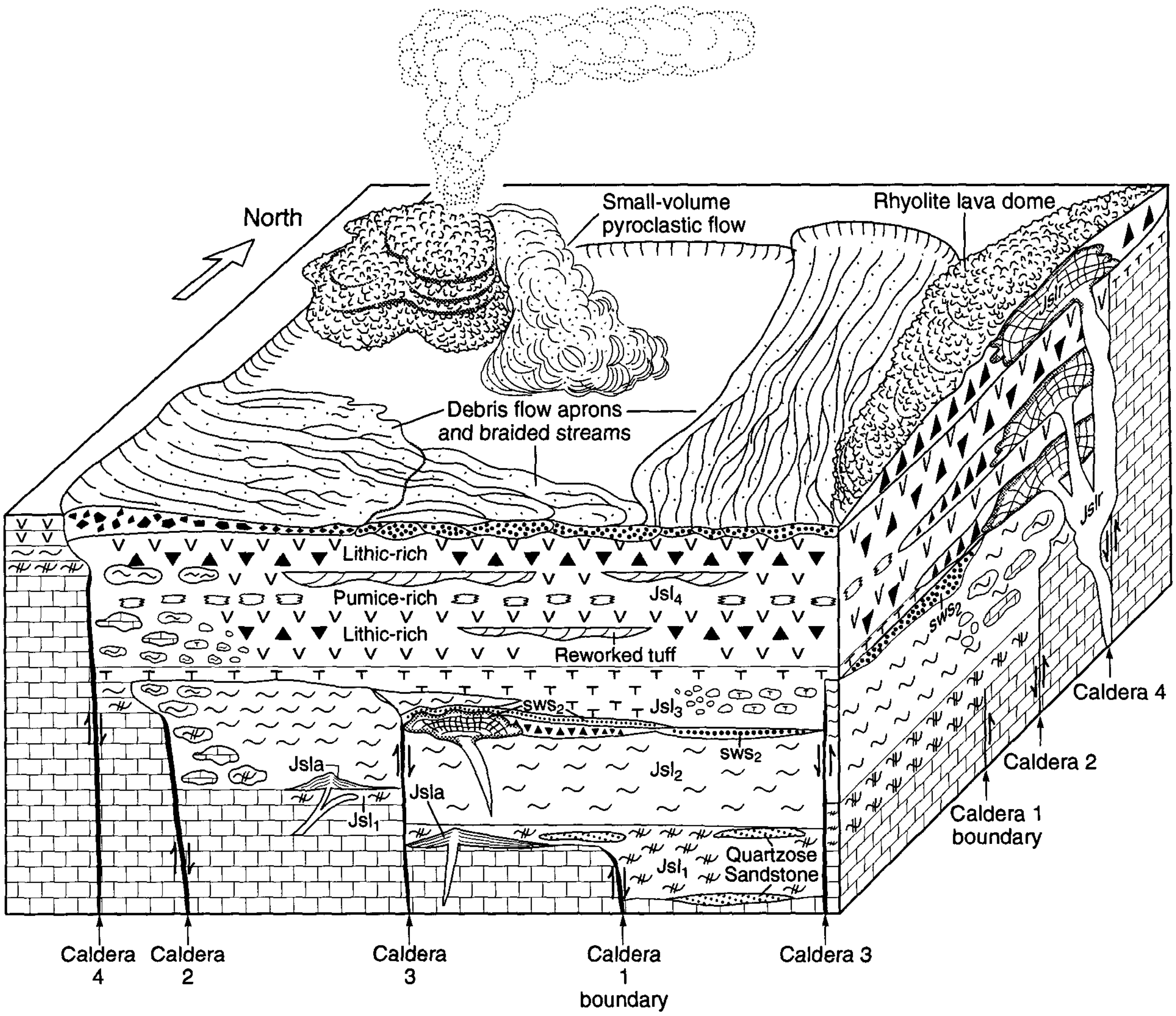



**Figure 11. Interpretive block diagram showing evolution of Lower Sidewinder volcanic series. Area depicted corresponds to Figure 10. Patterns are same as in Figure 3.**

erogeneous with regard to texture and composition, and appear to be on a relatively shallow level based on both plutonic and wall-rock textures and mineralogy (also see Solomon and Taylor, 1991). Quartz monzonite and granite constitute most of the plutons, but commonly associated small bodies of diorite, gabbro, and monzonite occur as border phases or inclusions (Table 1). The plutons are poorly dated. K-Ar cooling dates on hornblende and biotite range from 199 to 69 Ma, with emplacement ages thought to be ~160–200 Ma (Miller and Morton, 1980). Four $^{40}Ar/^{39}Ar$ hornblende dates from the Fry Mountains (Karish and others, 1987) range from 166 to 171 Ma. Dibblee (1960b, 1960c, 1964a, 1964b), Miller and Morton (1980), and Karish and others (1987) differentiated an older (probably Middle Jurassic) plutonic suite from a younger (probably Late Cretaceous) suite based on outcrop and mineralogical characteristics. On the basis of our additional mapping, and in the absence of further geochronological constraints, we have adopted this distinction (Table 1). The northwest-striking dikes of the 148 Ma Independence dike swarm cut the plutons and are extremely useful for distinguishing Jurassic from Cretaceous plutons (Fig. 2; Karish and others, 1987; James, 1989).

A period of erosion postdated intrusion of the mid-Jurassic plutons and predated emplacement of the Upper Sidewinder series. Although normal faults that cut the plutons have not been identified, it is possible that uplift and erosion of the plutons were related to continuing extension (Fig. 12). U-Pb ages of Lower Sidewinder ignimbrites are similar to K-Ar cooling ages of hornblende in plutonic rocks (described above), and Late Jurassic and Early Cretaceous biotite K-Ar cooling ages are locally preserved despite widespread Late Cretaceous resetting (Miller and Morton, 1980). This indicates that normal faulting, emplacement of plutons that intrude the faults, and partial unroofing of the plutons occurred within a short time span and thus may be related to the same tectonic event.

### Upper Sidewinder Volcanic Series
### Effusive Volcanism

Upper Sidewinder volcanic rocks are the youngest Mesozoic supracrustal rocks known in the west-central Mojave Desert, and facies relationships within them provide evidence

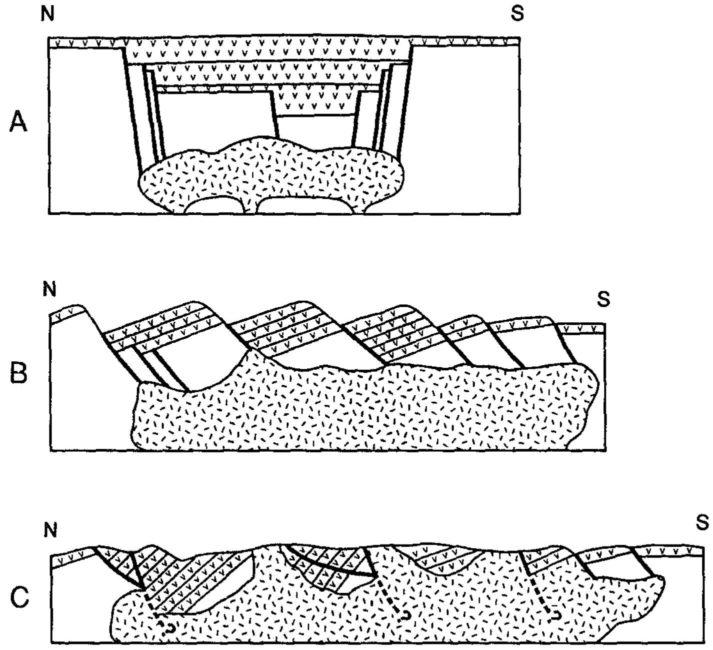



**Figure 12. Interpretive block diagram showing Middle Jurassic caldera collapse, pluton emplacement, and unroofing during north-south extension. (A) Multiple caldera collapse (see Fig. 11) and initial intrusion of Middle Jurassic plutons. (B) Main phase of north-south extension and continued intrusion. (C) Partial unroofing of batholith, possibly related to continuing extension.**

for the paleogeography of the region during Late Jurassic time (Fig. 13). Upper Sidewinder volcanic rocks are predominantly effusive and include felsic and mafic dikes and aphyric rhyolite intrusions at Quartzite Mountain and Black Mountain; felsic and mafic vent complexes at Ord Mountain, northwestern Rodman Mountains, and East Ord Mountain; and vent-proximal rhyolite lavas at North Black Mountain (Table 3).

Previous workers in the Ord and Fry Mountains (Karish, 1983; Karish and others, 1987) identified basaltic andesite lavas that overlie the tuff of Ord Mountain along an angular unconformity (Fig. 3) and termed this gently dipping sequence of lavas the Upper Sidewinder volcanic series. The unconformity between the ignimbrite and the lavas has ~100 m of relief along it. Mafic dikes intrude some of the basaltic andesite flows and are feeders to other flows. The dikes are part of a swarm in the Ord and Fry Mountains (Fig. 2) that ranges in composition from subalkaline to peralkaline and comprises a broadly bimodal suite of basalt, basaltic andesite, comendite, comenditic trachyte, and trachybasalt (Karish and others, 1987). We correlate "basalt porphyry" and "siliceous felsite" mapped by Dibblee (1964b) in the northwest Rodman Mountains (Fig. 3) with the dike swarm and associated lava flows and hypabyssal intrusive bodies. The dike swarm is considered to be a part of the Late Jurassic (~148 Ma) Independence dike swarm that trends northwesterly from southwestern Arizona to the eastern Sierra Nevada (Figs. 1 and 2; Karish and others, 1987; James, 1989). Miller (1978, 1981) interpreted the ignimbrites and andesites in the Quartzite Mountain area to be part of the Upper Sidewinder series because they are gently dipping, and she interpreted them to lie unconformably above the Fairview Valley Formation. Detailed mapping indicates that this contact is a fault, however, and the ignimbrites ($Jsl_1$, $Jsl_2$) are correlative with Lower Sidewinder sequences east of Quartzite Mountain (Fig. 3; see above).

**Vent Facies of the Upper Sidewinder Sequence.** The close association of lava flows, peperites, dikes, and hypabyssal bodies throughout the Upper Sidewinder volcanic series suggests that these deposits are vent and vent proximal facies. Karish (1983) documented feeder dikes to basaltic andesites in the Ord Mountains, and we have mapped similar intrusive-extrusive relationships in the northwestern Rodman Mountains (Fig. 3, Table 3; Schermer, 1993). Basaltic andesite porphyry lavas and shallow intrusions (Table 1, Jsub) in the Rodman Mountains commonly have a distinctive texture consisting of bimodal (1–2 mm and 1–2 cm) plagioclase phenocrysts. Peperitic margins with sedimentary rocks occur at the margins of shallow intrusions and lava flows. The porphyry complex in the Rodman Mountains also includes aphyric felsite (sf, Table 1) and plagioclase-phyric felsite (dpp, Table 1) composing subvertical dikes and irregularly shaped hypabyssal bodies. Mutual cross-cutting relations indicate that all three hypabyssal rock types (mafic and two felsic; Tables 1 and 3) are coeval. The Rodman Mountains suite appears to be crudely bimodal, as intermediate composition rocks are sparse, similar to the occurrences in the Ord and Fry Mountains.

Upper Sidewinder vent-facies volcanic rocks are interpreted to form the breccia complex of East Ord Mountain (Fig. 2) that was originally mapped as "latite porphyry breccia" and interpreted as a vent complex by Dibblee (1964a). Reconnaissance mapping by Karish (1983), Karish and others (1987), and in this study indicates that the complex is composed dominantly of volcanic breccias, hypabyssal silicic intrusive rocks, and basaltic to andesitic lavas and plugs. The breccias contain centimeter- to decimeter-scale clasts of felsic volcanic rocks, as well as less common basaltic fragments, tuff of Ord Mountain, and prevolcanic metasedimentary rocks. Many of the fragments strongly resemble the felsic dike rocks and hypabyssal intrusions that cut the breccias; thus, it seems likely that the breccias, dikes, lavas, and massive intrusions are coeval. Much of the breccia has a fine-grained basaltic or andesitic matrix, and so may be related to the basaltic andesite lavas. Small blocks of bedded sedimentary rock and possible fallout tuff occur amongst the intrusions; these may represent pieces of the wall rock surrounding the vent. Mapping indicates that the breccias and associated intrusions intrude the tuff of Ord Mountain and Jurassic(?) quartz monzonite exposed on the flanks of East Ord Mountain. The similarity of composition, lithofacies, and relative age between vent-facies rocks of East Ord Mountain and the Upper Sidewinder volcanic series in the Ord, Rodman (Table 3), and Fry Mountains (Karish and others, 1987) suggests that they are coeval.

Vent-facies Upper Sidewinder series rocks also occur at North Black Mountain and Black Mountain (Fig. 7, Table 3), where felsic rocks predominate over mafic rocks. Miller (1978, 1981) mapped a northwest-striking swarm of felsic dikes that cuts the Fairview Valley Formation and Lower Sidewinder ignimbrites (Fig. 7). Fine-grained

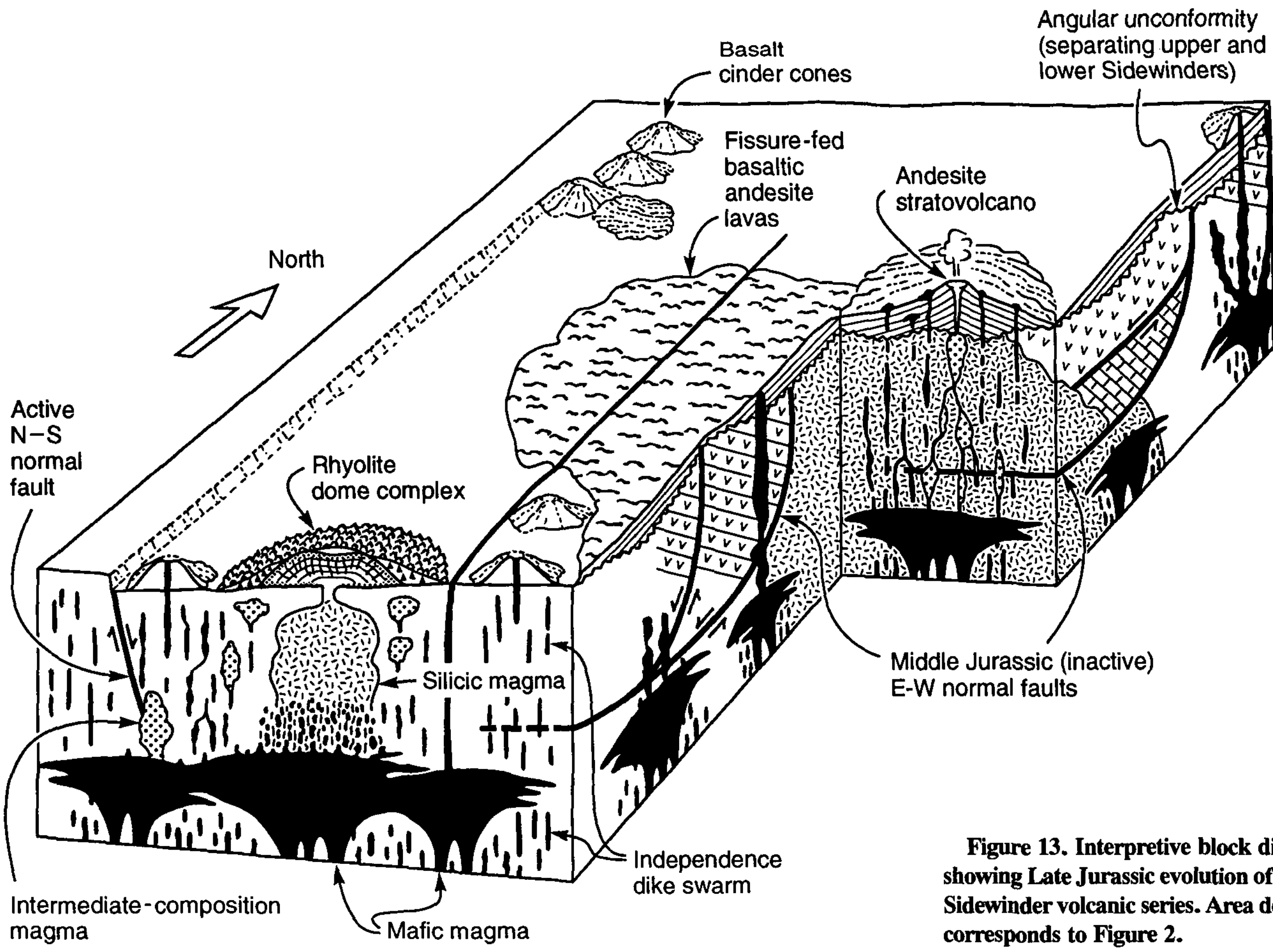



**Figure 13. Interpretive block diagram showing Late Jurassic evolution of Upper Sidewinder volcanic series. Area depicted corresponds to Figure 2.**

basaltic dikes occur but are not as abundant or well exposed as felsic dikes. Our mapping shows that both felsic and mafic dikes are coeval with and may be feeders to rhyolite lavas and basaltic lavas and/or sills that unconformably overlie and cross-cut tilted Lower Sidewinder tuffs and volcaniclastic sedimentary rocks at North Black Mountain (Tables 1 and 3; Fig. 7).

**Lava Flows and Sedimentary Rocks of the Upper Sidewinder Sequence.** Lava flows and sedimentary rocks in the Upper Sidewinder sequence are important markers of the Late Jurassic erosional surface (Fig. 13) and provide reference horizons for unravelling later deformational events. The steeply dipping latite ignimbrite at Ord Mountain is overlain unconformably by gently dipping basaltic andesite lava. The angular unconformity between the ignimbrite and lavas is also exposed discontinuously for ~4 km in the western part of the northwest Rodman Mountains, where the ignimbrite dips moderately to steeply, basaltic dikes are subvertical, and lava flows and associated sedimentary rocks are subhorizontal to moderately dipping (Schermer, 1993). Although Karish (1983) stated that the basaltic andesite also overlies eroded Jurassic quartz monzonite, we have found no location at Ord Mountain or in the Rodman Mountains where this relationship can be demonstrated. Basaltic andesite dikes cut the latite tuff and quartz monzonite and apparently are feeders to some of the lavas (Karish and others, 1987); thus, the lavas postdate the quartz monzonite. It remains unclear, however, how much erosion took place following tilting and pluton intrusion in the Ord-Rodman Mountain region.

The angular unconformity between Upper and Lower Sidewinder rocks appears to be of regional importance, as it also occurs in the western part of the study area at North Black Mountain. There, gently dipping rhyolite lava flows (fbr) of the Upper Sidewinder sequence unconformably overlie steeply dipping Lower Sidewinder volcanic rocks and Jurassic(?) biotite quartz monzonite. A thin sequence of gently dipping basalt lava flows (Jsub) intercalated with medium- to fine-grained sandstone and basalt-pebble breccia occurs locally between the Lower Sidewinder tuffs and the rhyolite lavas (Tables 1 and 3; Fig. 7).

**Age and Significance of Upper Sidewinder Volcanism.** Preliminary U-Pb age data, together with our stratigraphic and structural results, provide confirmation of previous workers' correlation of Upper Sidewinder volcanic rocks with the Late Jurassic Independence dike swarm (Fig. 1; Karish and others, 1987) and provide additional constraints on the time span and tectonic setting of the Mojave Desert segment of the dike swarm. There is some uncertainty as to whether the dike swarm is the same age along its entire length and whether mafic and felsic dikes are coeval (for example, Hopson, 1988). Only five silicic dikes have yielded reliable crystallization ages; samples of three dikes from the Sierra Nevada are nearly concordant at 147–

TABLE 3. SUMMARY OF CONTACT RELATIONS AND LATERAL VARIABILITY OF UPPER SIDEWINDER VOLCANIC ROCKS

| Area/Unit | Quartzite Mt. (QM), Silver Mt. (SM), Helendale Ridge (HR) | Black Mt. (BM), N Black Mt. (NBM) | Ord Mt. (Karish and others, 1987) | E Ord Mt. (Dibblee, 1964a, 1964b; Karish and others, 1987; this study) | NW Rodman Mts. |
|---|---|---|---|---|---|
| fbr* | QM, SM: tan to pale gray-green flow-banded aphyric rhyolite with large lithophysae intrudes $Jsl_2$† HR: dark gray aphyric to sparsely plag-phyric, locally flow-banded hypabyssal rhyolite possibly intrudes $Jsl_4$; contact n.e., may be younger shear zone | NBM: ~150-m-thick flow-banded aphyric rhyolite lava flow or flows unconfm on lower SWV, and J?qm dips 5°–6°N. Part of complex may be hypabyssal BM: NW-trending dikes, 1–10 m wide, aphyric and with up to 20% qtz + fsp | | | |
| sf | | | | Dikes, hypabyssal bodies, dome brx; locally with Jsub clasts | Dikes, hypabyssal bodies, dome brx; locally with Jsub clasts hypabyssal bodies are elongate, N-trending |
| dpp | | | | Dikes, hypabyssal bodies, dome brx; locally flow-banded, with inclusions of sf, Jsub, tuffs, sedimentary rocks | Dikes, hypabyssal bodies, dome brx; locally with Jsub, sf clasts local peperites hypabyssal bodies are elongate, N-trending |
| Jsub | Poorly exposed, altered basaltic dikes intrude FV, lower SWV; correlation with Jsub in other areas uncertain | NBM: ~10-m-thick fine-grained porphyritic amygdaloidal basaltic lava, flows reworked flow brx, possible sills | Lavas, dikes, local sedimentary rocks with basaltic lithic fragments. Dikes in NW- to N-trending swarm; cut lower SWV and Jqm, intruded by Kqm | Dikes, lavas, and brx with basaltic matrix, clasts of sf, dpp; intrudes lower SWV, Jqm | Lavas, dikes, hypabyssal intrusions; local sedimentary rocks with basaltic lithic fragments and peperites Dikes in N- to NNW-trending swarm |

*See Figure 3 and Table 1 for unit descriptions.
†$Jsl_2$, $Jsl_4$: lower Sidewinder ignimbrites; Jqm, Kqm quartz monzonites, see Table 1 for descriptions.
*Abbreviations*: brx = breccia; FV = Fairview Valley Formation; n.e. = not exposed; SWV = Sidewinder volcanic series; unconfm = unconformable.

149 Ma (Chen and Moore, 1979). Two dikes from the Mojave–southeast California part of the swarm yield lower intercept ages of 145–147 Ma (James, 1989; Fig. 9). Upper Sidewinder basaltic andesite dikes and lavas at Ord Mountain are considered to be coeval with the dike swarm (Fig. 1; Karish and others, 1987), but the sequence there has not been directly dated. Preliminary U-Pb zircon data from one of the felsic dikes of the swarm at Black Mountain (Fig. 7; lower intercept of 152 ± 3 Ma; Mattinson, Schermer, and Busby, unpub. data) are consistent with proposed correlations of the Upper Sidewinder dikes (and lava flows) of this area with the Independence dike swarm (Karish and others, 1987; Schermer and Busby-Spera, 1989). It is also significant that we have documented mutual crosscutting relationships that indicate felsic and mafic rocks are coeval. Taken together with the similarity in age of felsic dikes along the length of the dike swarm, these data suggest that both mafic and felsic dikes were intruded during a short-lived event. The short time span and consistent orientation of the dike swarm is thus more likely related to changes in the plate tectonic regime (see James, 1989, for a summary of possible events) than to a protracted Middle to Late Jurassic period of extension related to pluton intrusion within the arc batholith (Hopson, 1988). The dike swarm is interpreted to have been intruded during a period of regional northeast-southwest extension or transtension suggested by the trend of the dike swarm and local normal faults (Fig. 13). Evidence for extension is present at Ord Mountain, where north-northwest–striking faults interpreted as normal faults are locally intruded by pre–Late Cretaceous dikes (Karish, 1983), and in the Rodman Mountains, where a north-striking fault zone intruded by Upper Sidewinder basaltic andesites is interpreted to be a Middle or Late Jurassic normal fault (Schermer, 1993).

The presence of vent-facies and extrusive equivalents of the Independence dike swarm in the west-central Mojave Desert indicates preservation of a higher structural level than in other parts of the dike swarm. The absence of debris flows and volcaniclastic sedimentary rocks in the Upper Sidewinder series suggests that either local relief was low, and erosion minimal, or that all distal and reworked volcanic rocks have been removed by later erosion, leaving the more resistant lavas and hypabyssal parts of the volcanoes. The low relief on the unconformity and the gently dipping nature of the lava flows at Black Mountain, Ord Mountain, and northwest Rodman Mountains (except where affected by later folds) also suggest that relief was low. Individual units within the Upper Sidewinder series are not widespread, and thus we interpret them to have been erupted from multiple scattered small vents.

## IMPLICATIONS FOR ARC PALEOGEOGRAPHY AND REGIONAL TECTONICS

Exposures of Mesozoic supracrustal rocks are relatively rare in the Mojave Desert as a whole, and thus it is difficult to reconstruct its paleogeographic evolution. The west-central Mojave Desert region, however, contains thick sequences of Jurassic volcanic and sedimentary rocks that provide important constraints on the geologic history of the region. Our interpretation of detailed stratigraphic data on the Sidewinder volcanic series and its relations with other Mesozoic rocks in this area leads to the following interpretation of the paleogeographic evolution:

(1) The stratigraphy of the base of the volcanic section implies that the arc was a low-standing feature. The Lower Sidewinder volcanic series gradationally overlies the Fairview Valley Formation, suggesting shallow-marine conditions at the beginning of arc volcanism, rapidly succeeded by subaerial deposition. Quartzose sandstones in the upper part of the Fairview Valley Formation and the basal Sidewinder volcanic rocks appear to have a cratonal provenance.

(2) Volcanism during Lower Sidewinder time (~170 Ma) was mainly explosive and resulted in the emplacement of moderate- to large-volume (tens to hundreds of cubic kilometers) ignimbrites. A complicated eruption

history is manifested in complex mineralogical zonation of ignimbrites and multiple stages of collapse in overlapping or nested calderas. Four calderas appear to have formed during a time span short enough to prevent significant erosion or sedimentation between eruptive events.

(3) Eruption of the Lower Sidewinder volcanic rocks was followed by tilting of the entire succession, normal faulting, and intrusion of plutons. Map-scale normal faults are crosscut by both plutons and Upper Sidewinder volcanic rocks, thus limiting the age of this phase of extensional deformation to between ~167 Ma (minimum age of Lower Sidewinder ignimbrites) and ~148 Ma (age of Independence dikes), that is, late Middle Jurassic and/or Late Jurassic time. The age constraints on Jurassic plutons (166–171 Ma; Karish and others, 1987) suggest that normal faulting closely followed caldera formation and was coeval with and/or closely followed by pluton emplacement. The angular unconformity between the Lower Sidewinder and Upper Sidewinder series, together with the abundance of extensional structures and lack of contractional ones, indicates that a period of exhumation and erosion related to Middle Jurassic extension took place prior to eruption of the upper sequence.

The geometry and kinematics of faulting indicate that Middle Jurassic extension in this region had fairly consistent north-south orientation across the study area (Schermer, 1993). Although extension appears to be closely associated in time with the intrusion of plutons, pluton emplacement, which should produce varied extension directions, is an unlikely cause of the extension, although such a mechanism has been inferred for Jurassic rocks in the San Bernardino Mountains (Cameron, 1981; Miller and Cameron, 1982), and in the Sierra Nevada (for example, Tobisch and others, 1986; Longiaru, 1987). The north-south extension direction, together with approximately coeval east- and southeast-vergent thrusting to the north and northeast in the eastern Sierra (Dunne and Walker, 1993), the Cronese Hills (Walker and others, 1990a), the Tiefort Mountains region (Stephens and others, 1993), and possibly at Iron Mountain and Shadow Mountains (Fig. 1; Boettcher and Walker, 1990, 1993; Walker and others, 1990b), argues against simple arc-parallel or arc-perpendicular extension or contraction or a uniform and/or long-lived extensional (for example, Busby-Spera, 1988) or contractional (for example, Walker and others, 1990b) setting. The regional pattern of deformation and magmatism instead favors a sinistral oblique subduction environment with transpression and transtensional regimes in different orientations and locations along strike of the Middle Jurassic arc (Tosdal and others, 1989; Schermer and Busby-Spera, 1989; Busby-Spera and others, 1990a; Schermer, 1993). Thus, we would extend the model for Late Jurassic sinistral transtension inferred by others (Avé Lallemant and Oldow, 1988; Oldow and others, 1989; Saleeby and Busby-Spera, 1992) into Middle Jurassic time.

(4) During Late Jurassic time, emplacement of the northwest-trending Independence dike swarm along an ~500-km length of the Cordilleran arc appears to signal a major northeast-directed extensional or sinistral transtensional event (Moore and Hopson, 1961; Chen and Moore, 1979; James, 1989). Upper Sidewinder lavas are not typically tilted, and the only normal faults that cut the section are small-scale north- to northwest-striking faults (Karish, 1983; Schermer, 1993); thus, extension during this period was different in magnitude, style, and direction (northeast-southwest versus north-south) from the earlier event. The broadly bimodal and alkalic chemistry of the dike swarm in the west-central Mojave is consistent with a rift-related origin (Karish and others, 1987), although the chemistry of much of the dike swarm in the eastern Sierra Nevada (Chen and Moore, 1979; Hopson, 1988) argues for a subduction-related source area. Multiple scattered, small-volume effusive volcanic centers characterized the arc during Late Jurassic time.

(5) Prior to emplacement of the Late Cretaceous batholith, the Lower and Upper Sidewinder volcanic rocks (including Independence Dike Swarm) were folded together about northwest-trending axes and cleaved (Schermer and Busby-Spera, 1989; Schermer, 1993). Shortening of similar age and orientation has been reported from other parts of the Mojave Desert (see discussion in Schermer, 1993). The possibility exists that shortening in the western Mojave Desert resulted from dextral transpression along the Mojave–Snow Lake fault of Lahren and Schweickert (1989), although no northwest-trending Cretaceous strike-slip faults have been discovered in the western Mojave Desert. The Mojave–Snow Lake fault is inferred to have lain immediately west of the study area and to have transported a 200-km-long crustal block ~400 km northward in Early Cretaceous time. Saleeby and Busby (1993), however, point out that this reconstruction is inconsistent with batholithic petrochemical patterns and give evidence that rocks of the Snow Lake pendant were offset 200 km from the Inyo Mountains region, eliminating the need for a cryptic fault in the western Mojave Desert.

If Late Jurassic to Early Cretaceous intra-arc deformation in the Mojave Desert is related to that in other parts of the arc, the varied timing and kinematics of contractile events in the Mojave segment could not be attributed to the Nevadan Orogeny if the strict definition of its timing, 155 ± 3 Ma (Schweickert and others, 1984), is used. Wolf and Saleeby (1992, in press), however, propose that the Nevadan orogeny was a more protracted, transpressional-transtensional event that occurred from 160 to 137 Ma, and it is possible that deformation in the west-central Mojave Desert is part of a complex pattern of alternating transpression and transtension during Late Jurassic to Early Cretaceous oblique subduction.

## PRESERVATION OF CONTINENTAL VOLCANIC SEQUENCES

The stratigraphic and volcanologic characteristics of thick intra-arc supracrustal sequences that occur over an area of ~1,600 km$^2$ in the west-central Mojave Desert bear on the origin of volcanotectonic basins that accumulate and preserve continental volcanic sequences. During the early stages of volcanic activity, relief was low and the arc in this region may have been close to sea level. No ongoing tectonism is recorded that may have affected the accumulation of the earliest Sidewinder volcanic rocks. The major mode of accumulation and preservation of both volcanic and sedimentary rocks was due to caldera collapse, as indicated by the ~5-km-thick Lower Sidewinder section that consists principally of intracaldera ignimbrites and the lack of sedimentary deposits outside the calderas. Subsidence during Lower Sidewinder time thus occurred on a local scale and was directly related to magma withdrawal. No widespread outflow facies of the major caldera-forming ignimbrites ($Jsl_2$, $Jsl_4$) have yet been recognized. This may reflect (1) erosion of outflow facies, (2) eruptions characterized by a low or absent column (Fisher and Schminke, 1984), or (3) caldera subsidence that kept pace with or exceeded the eruption, so that little or no tuff could escape (Boden, 1986). Local preservation of outflow of two ignimbrites ($Jsl_1$, $Jsl_2$) argues against the third hypothesis. The presence of fallout tuffs throughout the tuff of Stoddard

Ridge argues against the second hypothesis. Thus, we believe the first hypothesis best explains the general lack of outflow facies. Since extracaldera sedimentary and volcanic sequences are a minor component of the Sidewinder volcanic series, subsidence outside the calderas appears to have been minimal.

Postcaldera extension and tilting caused both downdropping and uplift on a more regional scale. Preservation of Lower Sidewinder sequences was enhanced in relatively downdropped areas and Middle Jurassic plutonic rocks were unroofed in uplifted areas. The extension may have been related to batholith intrusion or, conversely, to the larger, plate-margin–scale tectonic regime that controlled the site of batholith emplacement. Oxygen isotope data from Middle Jurassic plutons that intrude the lower Sidewinder series and from other Jurassic plutonic rocks along the length of the batholith are interpreted to record extension on a plate-margin scale (Solomon and Taylor, 1991).

In the Upper Sidewinder series, vent and vent-proximal facies of composite cones and exogenous and endogenous domes were preserved. Low local relief is suggested by the absence of debris flow deposits and sedimentary rocks. The Independence dike swarm appears to be related to regional extension or transtension within the arc. The preservation of extrusive equivalents of the dike swarm in this region, unlike other areas, suggests some subsidence during this time. The absence of major normal faults and sedimentary basins of this age, however, argues against major extension and/or subsidence.

In conclusion, stratigraphic and structural data from the Mesozoic arc of the west-central Mojave Desert provide evidence that intra-arc basins formed at different times, on a variety of scales, and in a variety of tectonic regimes. Intermittent subsidence and/or extension occurred on both local (intracaldera; tens of kilometers) and regional (dike-swarm; hundreds of kilometers) scales over the ~25-m.y. span encompassing Lower and Upper Sidewinder time. The causes and rates of subsidence probably varied with time and along the length of the arc, and the west-central Mojave region may have occupied a transitional realm between a contractional regime to the north and a neutral or extensional regime to the south.

## ACKNOWLEDGMENTS

We are indebted to T. W. Dibblee, without whose maps and lithologic descriptions we would never have been able to undertake this project. E. L. Miller and C. Karish provided much advice, samples, and detailed maps in the initial stages of the project. Field assistance was provided by K. Maley, N. Beedle, L. Ames, and B. Adams. We thank the Southwestern Portland Cement Co. for granting permission to work in the Black Mountain area. Helpful discussions and reviews by N. R. Riggs, Eric James, and Dave Miller improved the manuscript, and field discussions with Doug Walker and Mark Martin helped to clarify many problems. This work was supported by a University of California President's Fellowship and National Science Foundation Grant EAR-9104915 to Schermer, EAR-8803769 and EAR-9018606 to Busby-Spera and J. M. Mattinson, and EAR-9219739 to Busby.

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Manuscript Received by the Society April 26, 1993
Revised Manuscript Received September 17, 1993
Manuscript Accepted October 13, 1993

Printed in U.S.A.