# Geologic Map of the Southern Inyo Mountains and Vicinity, Inyo County, California

By Paul Stone, Brian J. Swanson, Calvin H. Stevens, George C. Dunne, and Susan S. Priest

Pamphlet to accompany

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Cover: View of southern Inyo Mountains, California, showing eastward-overturned Upland Valley Syncline in sedimentary rocks of early to middle(?) Permian age. View is southwest toward Owens Lake playa and Sierra Nevada in distance.

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## Introduction

The Inyo Mountains are located in Inyo County, east-central California, between Owens Valley on the west and Saline Valley on the east (fig. 1). The map presented here encompasses the southeasternmost part of this range in which rocks of Paleozoic and Mesozoic age are continuously exposed, northwest of the late Cenozoic basaltic lava field of Malpais Mesa. The map area, centered on the high plateau of Conglomerate Mesa, extends from Owens Valley on the west to the Santa Rosa Hills, Lee Flat, and the Nelson Range on the east. The map area includes parts of the Cerro Gordo Peak, Nelson Range, Keeler, and Santa Rosa Flat 7.5' quadrangles.

The southern Inyo Mountains area is noteworthy for its exposures of regionally significant sedimentary and volcanic rocks, unconformities, and structural features that provide information critical for reconstructing the complex Paleozoic to Mesozoic paleogeographic and tectonic evolution of the southwestern United States (Dunne and others, 1978; Dunne, 1986; Snow, 1992; Stevens and others, 1997; Stone and others, 2000; Dunne and Walker, 2004; Stevens and Stone, 2005a, b). The area, which lies in the westernmost part of the Basin and Range province, also contains important exposures of upper Cenozoic volcanic rocks, sedimentary deposits, and faults. This geologic map primarily focuses on the Paleozoic and Mesozoic rocks and structural features, which we have mapped in considerable detail. Systematic detailed mapping of the upper Cenozoic rocks and sediments was beyond the scope of this study.

The primary sources for the geologic map presented here are previous maps by the authors (Stone, 1984; Stone and others, 1989, 2004; Swanson, 1996). We have modified and updated these original maps based on more recent field work, interpretation of aerial photographs, and paleontological studies. Most of the changes are in the vicinity of Conglomerate Mesa, where a number of faults have been reinterpreted, stratigraphic and structural details have been added in several places, and some outcrops have been assigned to different stratigraphic units than in the original mapping. Some information from older maps (McAllister, 1956; Hall and MacKevett, 1962; Stinson, 1977; Werner, 1979), modified on the basis of new field observations in some places, also was incorporated. Many rock units and structural features depicted on our map were first recognized by Merriam (1963) and Elayer (1974), whose mapping provided additional guidance to our field studies.

[Note on usage of the geographic name, “Santa Rosa Hills.” The 7.5' topographic base map used in this report labels two different areas where Paleozoic rocks are exposed as “Santa Rosa Hills”: (1) the prominent northwest-trending ridge near the southeastern corner of the map, bounded on the northwest by upper Cenozoic basalt; and (2) an area of low hills northwest of this basalt, 4 km east of Conglomerate Mesa. In this report, we restrict the geographic name “Santa Rosa Hills” to the southeastern ridge, in keeping with traditional usage as shown on earlier topographic maps. The hills east of Conglomerate Mesa, which were unnamed on earlier topographic maps, are herein informally called the “Fishhook hills” (following Stevens and Stone, 1988) in reference to the hook-shaped outcrop pattern of the Upper Mississippian Rest Spring Shale in this area. A clear geographic distinction between the Santa Rosa Hills and the Fishhook hills is important because of major differences between Mississippian to lowermost Permian rocks exposed in these two areas.]

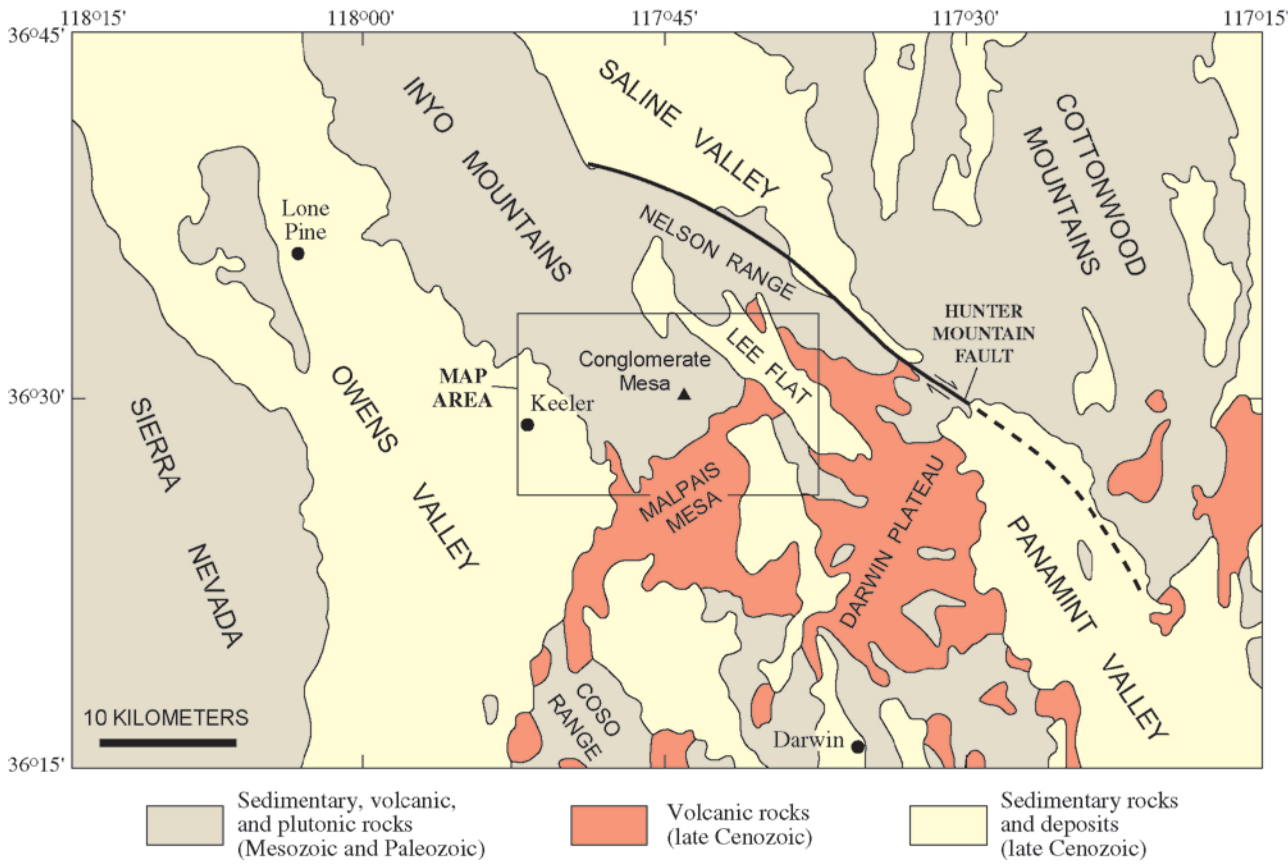


Figure 1. Location of map area in southern Inyo Mountains area, Inyo County, east-central California. Geology generalized from Jennings (1977). Trace of late Cenozoic Hunter Mountain Fault from Burchfiel and others (1987).

## Geologic Time Divisions

The divisions of geologic time used in this report are those recently recommended by the U.S. Geological Survey Geologic Names Committee (2007). The recommended divisions include the Cisuralian, Guadalupian, and Lopingian epochs/series, which supersede the Early or Lower, Middle, and Late or Upper Permian, respectively, and the Llandovery, Wenlock, Ludlow, and Pridoli epochs/series, which collectively supersede the Early or Lower, Middle, and Late or Upper Silurian. For these periods, the Geologic Names Committee recommendations include the alternative use of informal terms such as early Permian and upper Silurian. In this report, which emphasizes the Permian stratigraphy and geologic history, we generally use the formal terms Cisuralian, Guadalupian, and Lopingian, but we also use the informal terms early or lower, middle, and late or upper Permian where appropriate. We additionally use the informal term early Silurian. For the other pre-Cenozoic periods, in keeping with the Geologic Names Committee recommendations, formal epoch or series names utilizing the terms Early or Lower, Middle, and Late or Upper continue to be used.

Other geologic time divisions used in this report are the Wolfcampian, Leonardian, and Roadian ages or stages, which are equivalent to the early or lower Cisuralian, late or upper Cisuralian, and early or lower Guadalupian epochs or series, respectively.

# Pre-Cenozoic Biostratigraphic and Geochronologic Framework

Paleozoic and Mesozoic rocks exposed in the map area range in age from Ordovician to Jurassic and possibly Cretaceous for the youngest intrusive rocks (see Description of Map Units). The ages of these rocks are based on paleontological and geochronologic studies that have been conducted over a period of several decades.

The basic ages of Ordovician to Triassic sedimentary rocks exposed in and near the map area were established by paleontological studies in conjunction with early geologic mapping investigations (McAllister, 1956; Hall and MacKevett, 1962; Merriam, 1963). Later studies have refined the ages of many of these rocks. Miller (1975, 1976) refined the ages of the Upper Ordovician to Lower Devonian rocks on the basis of conodonts. Stevens and others (1996) updated the biostratigraphic framework of the Mississippian rocks, also based primarily on conodonts, and Titus (2000) has presented a detailed account of the regional Late Mississippian ammonoid biostratigraphy. Detailed studies of fusulinids (Magginetti and others, 1988; Stevens and others, 2001; Stevens and Stone, 2009a, c) have refined the ages of the Pennsylvanian and lower Permian rocks. Corals (Stevens and Stone, 2009b) and ammonoids (Baker, 1986; see Appendix) have also been described from lower Permian rocks in the map area. Stone and others (1991) updated the biostratigraphic framework of the Triassic Union Wash Formation on the basis of conodonts, and Stone and others (2000) clarified the biostratigraphic relations of rocks near the Permian-Triassic boundary on the basis of fusulinids, conodonts, and ammonoids.

Younger Mesozoic rocks exposed in and near the map area consist of the Jurassic Inyo Mountains Volcanic Complex, which unconformably overlies the Union Wash Formation, and various intrusive bodies. Dunne and Walker (1993) and Dunne and others (1998) have clarified the age of the Inyo Mountains Volcanic Complex on the basis of uranium-lead (U-Pb) zircon dating, and the ages of some Jurassic intrusive rocks, notably the Hunter Mountain Quartz Monzonite and dikes of the Independence dike swarm, also have been determined through U-Pb zircon dating (Dunne and others, 1978). Most of the intrusive units in the map area, however, have not been dated.

# Geologic Summary

## Ordovician to Earliest Permian

In early to middle Paleozoic time the southern Inyo Mountains area was part of the western continental shelf of North America. Ordovician to Devonian shallow-water marine carbonate and subordinate quartzose strata exposed in the map area accumulated on this broad, southwest-trending shelf (Stevens, 1986). During the latest Devonian to Mississippian Antler orogeny, lower Paleozoic oceanic strata were thrust onto the western edge of the continental shelf to form a marginal uplifted belt (Burchfiel and Davis, 1975; Miller and others, 1992). Antler-age deformation is not recognized in the map area, but the Upper Mississippian Rest Spring Shale is considered part of a siliciclastic wedge derived from the Antler belt and deposited in its foreland basin (Stevens and others, 1997). The inferred trace of the southwest-trending Late Mississippian shelf margin crosses the eastern part of the map area (fig. 2), between the Fishhook hills and the Santa Rosa Hills, where it is marked by the southeastern limit of the basinal Rest Spring Shale and the northwestern limit of the shallow-water Santa Rosa Hills Limestone.

In Pennsylvanian time, the southwestern part of the shelf subsided and a new shelf margin, trending southeastward down the present axis of Panamint Valley, was established (fig. 2). Calcareous turbidites of the Pennsylvanian to lowermost Permian Keeler Canyon Formation were deposited in a basin that developed west of the shelf (Keeler Basin of Stevens and others, 2001). This change in orientation and position of the shelf margin is inferred to have been related to truncation of the continental margin to the west along a southeast-trending zone of transform faulting (Stone and Stevens, 1988; Stevens and others, 2005).

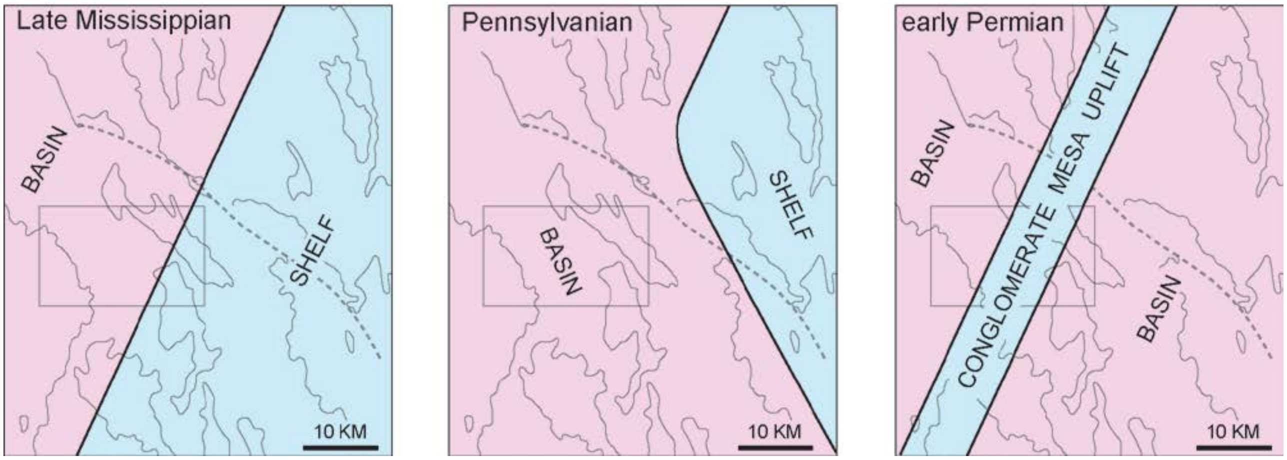


Figure 2. Maps showing Late Mississippian to early Permian paleogeographic evolution of the southern Inyo Mountains area. Rectangle denotes area of geologic map; range outlines are the same as on figure 1. Dotted line is trace of Cenozoic Hunter Mountain Fault, on which 10 km of right-lateral displacement has been restored based on the interpretations of Burchfiel and others (1987). See text for discussion of paleogeographic evolution.

## Middle Early Permian to Late Permian

Beginning in middle early Permian time, thrust faulting and folding near the east margin of the Keeler Basin formed a north-northeast-trending ridge called the Conglomerate Mesa Uplift (fig. 2), which is thought to have extended through the map area and into the Cottonwood Mountains (Stone and Stevens, 1988; Stevens and Stone, 2007). This deformation began with development of the structurally complex Fishhook Thrust Fault (Stevens and Stone, 1988; Stone and others, 1989). This fault duplicated the Keeler Canyon Formation and was subsequently folded as units 1–3 of the lower and middle(?) Permian sedimentary rocks of Santa Rosa Flat were deposited on the east flank of the resulting antiform (fig. 3). Subsequent pulses of folding to the west further elevated the Conglomerate Mesa Uplift until more than 3 km of strata assigned to the sedimentary rocks of Santa Rosa Flat ultimately accumulated and pinched out against the uplift (fig. 4). Deformation continued into the late Permian, when the youngest units of the sedimentary rocks of Santa Rosa Flat were folded by the eastward-overturned Upland Valley Syncline of Swanson (1996).

As shown in cross section *B-B′*, we consider the Fishhook Thrust Fault to be the eastern extension of the Morning Star Thrust Fault (fig. 5), which we interpret as a décollement that separates the Rest Spring Shale from the Keeler Canyon Formation throughout much of the southern Inyo Mountains (Elayer, 1974; Stevens and Stone, 2005a). We further interpret the Morning Star Thrust Fault as continuous with the southeast-directed Last Chance Thrust Fault that is widely exposed north of the area shown in figure 1 (Stewart and others, 1966; Stevens and Stone, 2005a). The Last Chance Thrust Fault places Neoproterozoic and lower Paleozoic rocks above the Rest Spring Shale, with the upper-plate strata interpreted to have formed a large fault-bend anticline (fig. 5). Southeast of the anticline, we infer the thrust surface to have flattened into a bedding-plane fault (represented by the Morning Star Thrust Fault) along which the Rest Spring Shale was overridden by the Keeler Canyon Formation. Farther southeast, we interpret the thrust surface (represented by the Fishhook Thrust Fault) to have ramped through the Keeler Canyon Formation, duplicating the section as the Conglomerate Mesa Uplift began to develop.

The structure of the Conglomerate Mesa Uplift shown in figure 5 differs from that in the previous model of Stevens and Stone (2005a). In that model, the uplift was speculated to consist of an antiformal stack of relatively thin thrust sheets underlain in the subsurface by a décollement continuous northwestward with the Morning Star Thrust Fault. The upper plate of the Fishhook Thrust Fault was interpreted to represent the uppermost part of the antiformal stack, and the inferred Lee Flat Thrust Fault of Stevens and Stone (1988) and Stone and others (1989) was interpreted to represent the underlying décollement. More recent analysis, however, suggests that neither the antiformal stack nor the Lee Flat Thrust Fault is needed to explain the subsurface structural geometry, leading to the simpler model shown in figure 5.

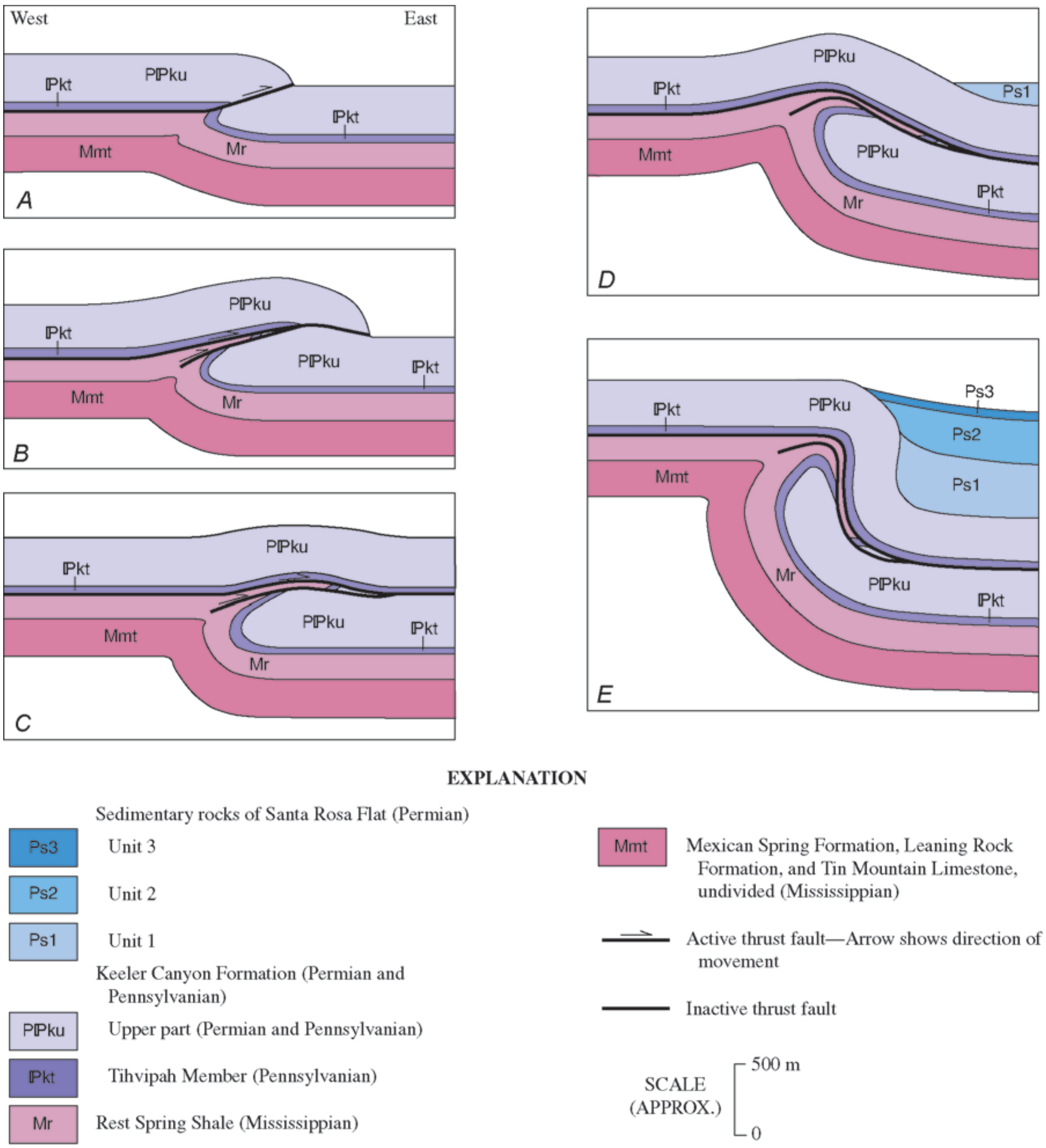


Figure 3. Evolution of Fishhook Thrust Fault and related folds in early Permian time. *A*, Thrust fault, flat to the west where it separates Rest Spring Shale and Keeler Canyon Formation, ramps eastward through Keeler Canyon Formation where an overturned fold begins to develop. The flat fault to the west is the Morning Star Thrust Fault; the fault that ramps through the Keeler Canyon Formation is the Fishhook Thrust Fault. *B*, upper plate of the Fishhook Thrust Fault begins to override lower plate, duplicating Keeler Canyon Formation; secondary thrust fault and overturned syncline develop in lower plate. *C*, eastward movement of upper plate continues. *D*, fault movement ceases and antiformal folding begins; unit 1 of sedimentary rocks of Santa Rosa Flat begins to be deposited on east flank of antiform. *E*, continued folding deforms inactive thrust faults and associated strata into an asymmetric antiform; units 1-3 of sedimentary rocks of Santa Rosa Flat are deposited in the resulting basin to the east. Later westward tilting, probably during the Mesozoic, would rotate all rocks and structural features to their present attitudes (see cross section *B-B'*).

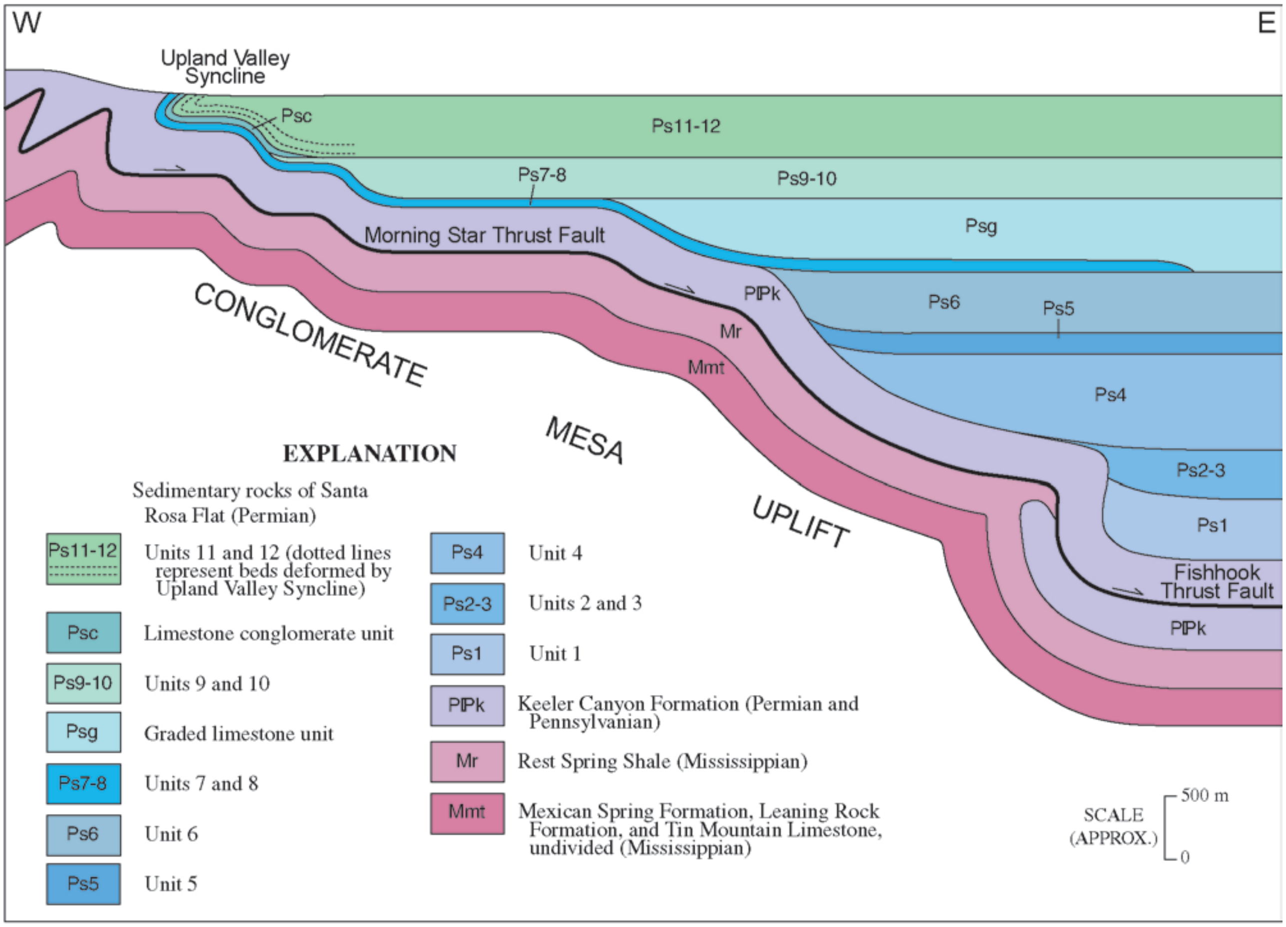


Figure 4. Schematic cross section showing inferred structural architecture of east side of the Conglomerate Mesa Uplift (CMU) and onlapping relations of Permian sedimentary rocks of Santa Rosa Flat (SRF) prior to Early Triassic(?) deposition of member C of the Conglomerate Mesa Formation. Development of the CMU began with early Permian duplication of Keeler Canyon Formation on the Fishhook Thrust Fault and subsequent folding that caused the westward depositional pinchouts of SRF units 1–3 (see fig. 3). Later deformation during early to middle(?) Permian time produced a series of westward-younging monoclines that controlled the western depositional pinchouts of progressively younger SRF units on the evolving east side of the CMU. Late Permian (or earliest Triassic) Upland Valley Syncline further modified the CMU following deposition of the youngest SRF units.

This analysis is largely based on the structural interpretation shown in cross section *B-B′*, the eastern part of which crosses the Fishhook hills where the antiformally folded Fishhook Thrust Fault is exposed. As indicated in cross section *B-B′*, the Fishhook Thrust Fault is inferred to be synformally folded in the subsurface east of the antiform based on bedding attitudes of exposed strata in units 1–3 of the sedimentary rocks of Santa Rosa Flat. The Keeler Canyon Formation and older units in the lower plate of the Fishhook Thrust Fault are depicted as forming a syncline concordant with the thrust fault. This interpretation differs from previous interpretations in which the Lee Flat Thrust Fault was inferred to transect the rocks below the Fishhook Thrust Fault, juxtaposing the lithologically distinct Mississippian to lowermost Permian sequences of the Santa Rosa Hills and the Fishhook hills (Stevens and Stone, 1988; Stone and others, 1989). The projected surface traces of the lower-plate units in the eastern limb of the syncline are closely aligned with the coeval units exposed in the Santa Rosa Hills. The implied structural continuity casts doubt on the existence of the Lee Flat Thrust Fault and supports the subsurface geometry depicted in cross section *B-B′*.

On the other hand, the interpretation that no fault juxtaposition takes place between the Santa Rosa Hills and the Fishhook hills makes it more difficult to explain the substantial changes in lithology and thickness between coeval Mississippian to lowermost Permian units in these two areas (see Description of Map Units). These changes from the Santa Rosa Hills to the Fishhook hills include the following: (1) the pure limestone of the Santa Rosa Hills Limestone is replaced by siltstone of the Mexican Spring Formation; (2) the thin, quartzitic Indian Springs Formation is replaced by the much thicker Rest Spring Shale that lacks quartzite; and (3) the disconformity between the Indian Springs Formation and the Santa Rosa Hills Limestone is replaced by a conformable contact between the Mexican Spring Formation and Rest Spring Shale. In addition, the lower coarse-grained unit of the upper part of the Keeler Canyon Formation (unit ℙkuc), which disconformably overlies the Tihvipah Member in the Santa Rosa Hills, is not recognized in the Fishhook hills, where relatively fine grained rocks of the upper part of the Keeler Canyon Formation (unit PℙPku) conformably overlie the Tihvipah Member. Because of the magnitude of these changes in units that span such a long period of time, and over a distance of only about 4 km, juxtaposition by subsurface faulting must still be considered possible despite the lack of supporting structural evidence.

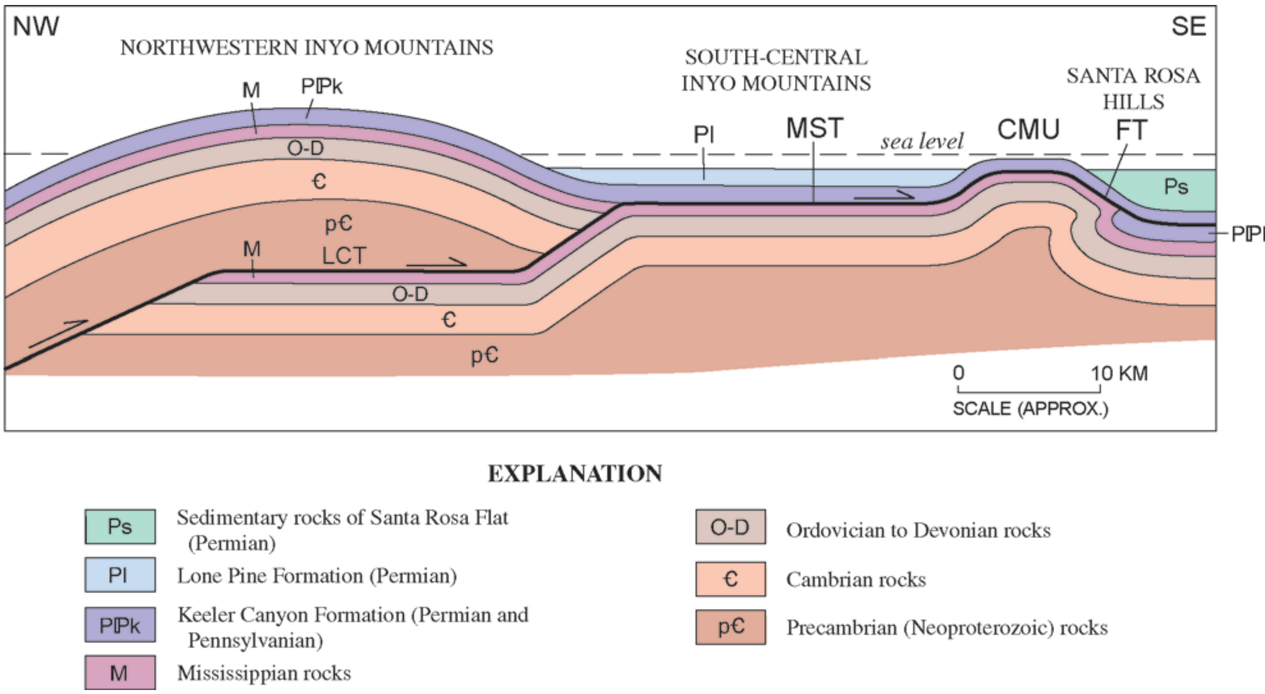


Figure 5. Cross-sectional model showing structural relations between the Last Chance, Morning Star, and Fishhook Thrust Faults (LCT, MST, and FT, respectively) as interpreted in this report. CMU = Conglomerate Mesa Uplift. Modified from Stevens and Stone (2005a).

Our structural model of the Last Chance, Morning Star, and Fishhook Thrust Faults (fig. 5), like the similar model of Stevens and Stone (2005a), requires a relatively thin upper plate, composed mainly of Keeler Canyon Formation, to have been transported as much as 30 km southeastward on the Morning Star Thrust Fault while remaining more or less structurally intact. It is uncertain whether or not this requirement is realistic. Despite this and other uncertainties, however, the model is consistent with the known geologic relations in the region and offers the most reasonable explanation yet proposed for the apparent lack of continuity of the Last Chance Thrust Fault across the northwestern Inyo Mountains as discussed by Stevens and Stone (2005a).

Lower and middle(?) Permian strata that postdated the initiation of thrust faulting and folding were deposited in two basins separated by the Conglomerate Mesa Uplift (figs. 2, 5). The two basins received deposits of contrasting sedimentary facies: the fine-grained Lone Pine Formation on the northwest and the generally coarser grained sedimentary rocks of Santa Rosa Flat on the southeast. Strata representing both basins are recognized throughout a large region between Owens Valley and Death Valley (Stone and Stevens, 1988), but detailed relations of strata deposited close to the Conglomerate Mesa Uplift are preserved only in the area of this report.

The lithologically diverse sedimentary rocks of Santa Rosa Flat (fig. 4) had a complex history that began with deposition of deep-water marine turbidites (units 1–6). Units 1–3 pinched out against the north-northeast-trending Fishhook fold complex, whereas units 4–6 were deposited across the Fishhook complex and presumably pinched out against a younger fold that developed farther west (figs. 3, 4). The pinchouts of units 4–6 are not exposed, but they are inferred to take place in the subsurface (see cross sections *A-A′* and *B-B′*). Folds that formed during this early stage of uplift are observed or inferred to have trended north-northeast, parallel to the orientation of the Conglomerate Mesa Uplift. Following deposition of unit 6, shallow-water marine carbonate strata (units 7 and 8) accumulated across the Conglomerate Mesa Uplift, which we interpret to have been a relatively flat carbonate platform at this time. Turbidites (graded limestone unit) continued to be deposited southeast of this platform, overlying rocks of unit 7 in some places where the edge of the platform apparently was downwarped (fig. 4).

After deposition of these carbonate strata, the Conglomerate Mesa Uplift underwent further deformation by folds observed or inferred to have trended north-northwest. As this deformation took place, clastic and minor carbonate strata (units 9–12 and the limestone conglomerate unit) accumulated in environments that gradually changed through time from shallow-water marine to nonmarine. These strata are characterized by lateral facies changes and pinchouts caused by syndepositional folding (fig. 4). Deformation culminated in development of the Upland Valley Syncline, which folds rocks as young as unit 12b of the sedimentary rocks of Santa Rosa Flat, and additional folds in the Keeler Canyon Formation to the west. Rocks in the overturned limb of the Upland Valley Syncline are unconformably overlain by the Lower to Middle(?) Triassic Union Wash Formation (Swanson, 1996). This folding, which is therefore limited to the latter part of the Permian and possibly the earliest Triassic, is thought to have been part of a regional deformational event (Stevens and Stone, 2005b).

Structural features of this age probably include the Inyo Crest Thrust Fault of Swanson (1996), which cuts the Keeler Canyon Formation northwest of the Upland Valley Syncline. Stevens and Stone (2005b) considered the Inyo Crest Thrust Fault to be of regional extent and significance, but reevaluation of its map relations in the study area suggests to us now that this fault is a relatively minor feature of only local importance. We continue to regard the Upland Valley Syncline, however, as part of a regional zone of overturned folds and thrust faults that extends at least 75 km northward from the map area (Stevens and Stone, 2005b).

## Triassic to Cretaceous

Following late Permian deformation and uplift, an erosional unconformity was beveled across the southern Inyo Mountains area prior to deposition of the nonmarine, conglomeratic member C of the Conglomerate Mesa Formation (unit TRcc) of probable earliest Triassic age. This coarse-grained clastic sedimentation was followed in the Early and Middle(?) Triassic by regional subsidence of the continental margin and deposition of the marine Union Wash Formation.

Withdrawal of marine waters from the region after deposition of the Union Wash Formation was followed in the Jurassic by volcanism and volcanogenic sedimentation represented by the Inyo Mountains Volcanic Complex. This volcanic activity, presumably caused by eastward subduction of oceanic crust beneath a fully developed convergent margin (Dunne and Walker, 1993; Dunne and others, 1998), marked one growth phase of the Sierran magmatic arc, the core of which lay west of the map area. Intrusive outliers of the arc (dikes, sills, and plutons) sporadically invaded the southern Inyo Mountains area during Jurassic and Cretaceous time. Late Jurassic dikes of the Independence dike swarm (Chen and Moore, 1979; Carl and Glazner, 2002) are extensively exposed in the map area.

Also during this time, the East Sierran Thrust System developed along the eastern margin of the Sierra Nevada batholith (Dunne, 1986; Dunne and Walker, 2004). Deformation spanned a long time interval that began prior to 188 Ma (Early Jurassic) and continued past 140 Ma (Early Cretaceous), broadly synchronous with the Nevadan orogeny farther west. Most of the deformation probably took place in the Late Jurassic between 152 and 148 Ma (Dunne and Walker, 2004).

The East Sierran Thrust System is characterized by pervasive, northwest-trending, northeast-vergent structural features. In the map area this deformation is represented by thrust faults, folds with accompanying cleavage, and general ductile flattening. The most significant thrust faults, including the Flagstaff Thrust Fault of Elayer (1974) that places the Permian Lone Pine Formation above the Jurassic Inyo Mountains Volcanic Complex, are on the west flank of the southern Inyo Mountains, but folds and cleavage extend across the range. Estimated minimum horizontal shortening on the East Sierran Thrust System in the southern Inyo Mountains is about 9 km (Dunne and Walker, 2004). Post-Early Triassic reverse faults on the west flank of Conglomerate Mesa may be tectonically related to the East Sierran Thrust System.

A large, unusual structural feature of Mesozoic age in the eastern part of the map area is defined by a zone of faulting that flanks Conglomerate Mesa on its western, southern, and eastern sides (fig. 6). We call this feature the Malpais Fault, a name first used by Elayer (1974) for a segment of this fault south of Conglomerate Mesa. This fault

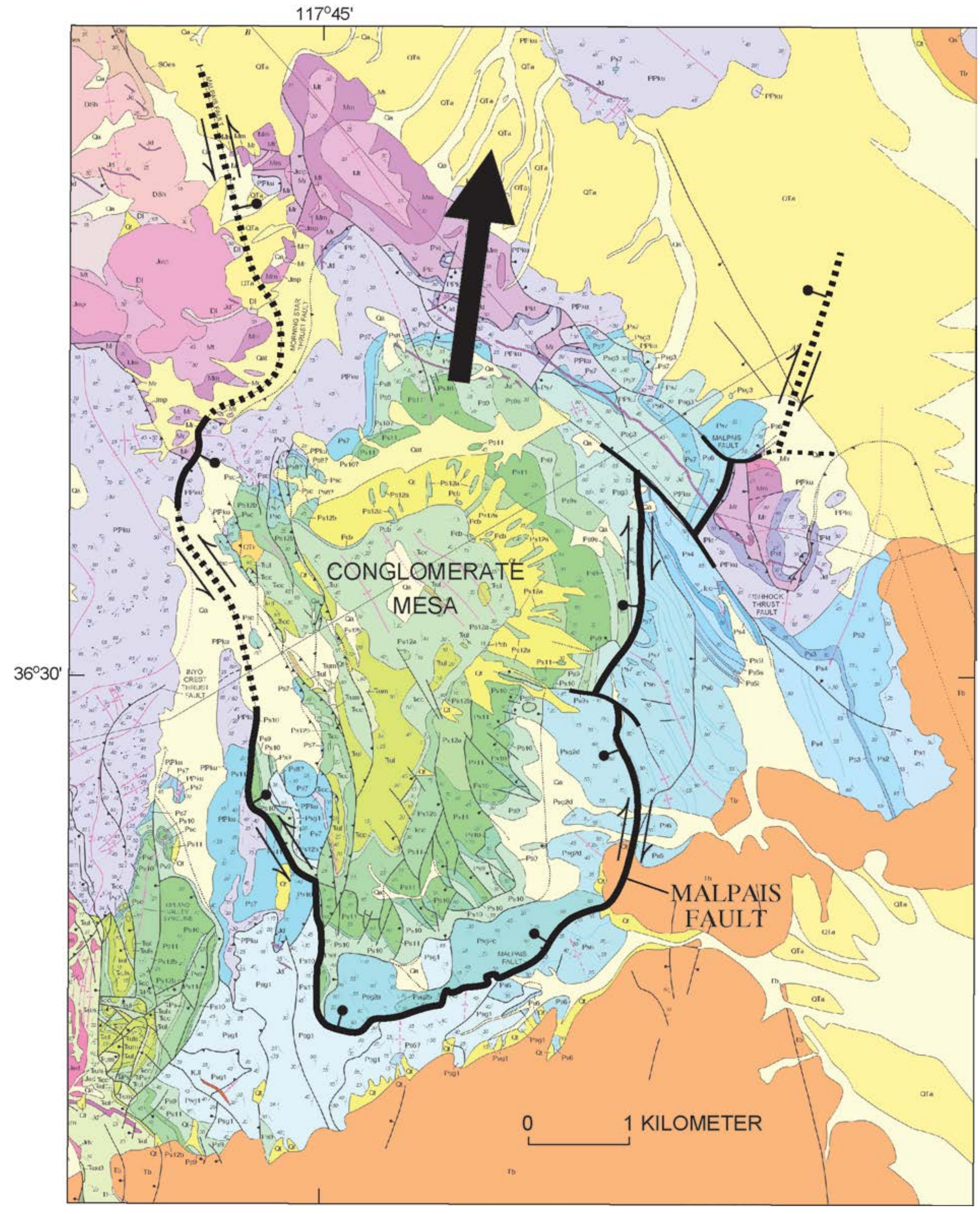


Figure 6. Reduced part of the geologic map of this report, showing proposed trace of the Malpais Fault. Fault is interpreted as a scoop-shaped dislocation surface on which the hanging wall (rocks inside the fault trace) moved relatively down and northward as indicated by strike-slip arrows and bar-and-ball symbols. Large, thick arrow shows inferred general transport direction of hanging wall relative to footwall. Note lateral offsets of Malpais Fault on younger crossfaults east of Conglomerate Mesa. Dotted fault segments are concealed.

strikes east-southeast and dips gently to moderately northward along this southern segment. It bends sharply northward both east and west of Conglomerate Mesa, where it dips steeply inward toward the mesa. The nature of this fault is somewhat speculative, but we interpret it as a scoop-shaped dislocation surface along which the structural block inside the U-shaped fault trace (the hanging wall) moved down and northward relative to the footwall rocks outside (fig. 6). In this model, the segment south of Conglomerate Mesa is viewed as a normal fault, and the segments east and west of the mesa are viewed as oblique strike-slip faults. Stratigraphic and structural markers suggest that the hanging-wall block was displaced about 0.5 to 1 km relatively northward. The exact age of faulting is not known, but the fault postdates the Triassic Union Wash Formation and is cut by a dike of presumed Jurassic age (unit Jd). The fault is also interpreted to cut the reverse faults west of Conglomerate Mesa. If those faults are coeval with the East Sierran Thrust System, the Malpais Fault is Jurassic. Its regional tectonic relations, however, are unknown.

## Late Cenozoic

The late Cenozoic history of the southern Inyo Mountains area has been marked by uplift, basaltic volcanism, and alluvial-fan sedimentation related to Basin and Range extensional tectonism (Snow and Wernicke, 2000). Initial uplift of the southern Inyo Mountains relative to the adjacent valleys, presumably related to normal faulting, probably predated or accompanied deposition of middle to late Miocene alluvium (unit Tf and older parts of unit QTa) on both sides of the range (Conrad, 1993; Stone and others, 2004). Basaltic volcanism took place in late Miocene to Pliocene time (Larsen, 1979; Bacon and others, 1982) and was followed by more faulting and alluvial-fan deposition. On the west side of the southern Inyo Mountains, west-dipping normal faults cut basalt in several places. Other faults cut alluvium assigned to unit QTa along the range front east of Keeler, and geophysical data (Pakiser and others, 1964) indicate a major range-front fault at depth. The most prominent fault that cuts unit QTa in this part of the map area is an oblique right-lateral fault with the east side down (Swanson, 1996; Stone and others, 2004; Slemmons and others, 2008; Jayko, 2010). A detailed study by Bacon and others (2005) indicated activity as young as late Pleistocene or possibly Holocene along this fault trend. On the east side of the Inyo Mountains, a pair of faults, both marked by scarps with the west side down, cut fanglomerate of unit QTa in the northern part of Lee Flat. Geodetic data (Savage and Liskowski, 1995) indicate that northwest-directed extensional tectonism continues in the vicinity of the map area today.

# DESCRIPTION OF MAP UNITS

### SURFICIAL DEPOSITS AND BASALT

mt **Mine tailings**

Qa **Alluvium (Quaternary)**—Unconsolidated to weakly consolidated deposits of locally derived gravel and sand. Unit includes deposits of washes, valleys, and alluvial fans that probably range from Holocene to late Pleistocene in age based on criteria discussed by Bull (1991) and Jayko (2010). The older deposits of this unit commonly show bar and swale surface morphology and other evidence of relatively recent deposition

Qt **Talus (Quaternary)—**Unconsolidated to weakly consolidated accumulations of angular gravel deposited at the bases of steep slopes under influence of gravity. Probably largely Holocene and late Pleistocene in age

Qat **Alluvium and talus, undivided (Quaternary)**

Qp **Playa deposits of Owens Lake (Quaternary)—**Unconsolidated mud and evaporites, commonly saturated with brine

Qpm **Playa-margin deposits of Owens Lake (Quaternary)—**Unconsolidated sand and silt, locally including beach deposits and eolian dunes (Jayko, 2010)

QTa **Old alluvium and fanglomerate (Quaternary and Tertiary)—**Weakly to firmly consolidated deposits of locally derived gravel, sand, and silt forming dissected ridges and terraces. Commonly cemented by calcium carbonate. Unit ranges from deeply dissected deposits as old as middle Miocene in age (Stone and others, 2004) to less dissected deposits forming well-developed desert pavements that could be as young as middle or late Pleistocene, based on criteria discussed by Bull (1991) and Jayko (2010). Older parts of unit predate Tertiary basalt (unit Tb); younger parts postdate the basalt. Some deposits contain basalt clasts. Unit includes the fanglomerate of Slate Canyon and the fanglomerate of Bonham Canyon of Stone and others (2004), which contain ash beds dated as late Miocene (about 9 to 6 Ma) and middle Miocene (13.6±0.5 Ma), respectively (A.M. Sarna-Wojcicki, written commun., in Stone and others, 2004; Conrad, 1993). Includes the following subunit:

QTas **Silt beds (Quaternary or Tertiary)**—Weakly consolidated beds of grayish-white silt that interfinger with dissected deposits of alluvial gravel (unit QTa). Present only in a small area on west side of the Inyo Mountains; interpreted as lake deposits (Swanson, 1996). Local stratigraphic and structural relations indicate that the silt beds and the interfingering alluvium are younger than adjacent Tertiary fanglomerate (unit Tf) and basalt (unit Tb) (Swanson, 1996)

QTr **Rubble (Quaternary or Tertiary)**—Weakly consolidated deposit of unsorted, angular clasts of reddish-brown conglomerate and sandstone. Possibly the remnants of an ancient landslide deposit derived from nearby altered (jasperized) member C of the Conglomerate Mesa Formation (₸cc)

Tb **Basalt (Tertiary)**—Basalt flows, dikes, and pyroclastic rocks. Flows and dikes consist of dark-gray basalt that typically contains small phenocrysts of olivine, plagioclase, and augite in an aphanitic groundmass. Some flows are amygdaloidal and vesicular. Pyroclastic rocks, most of which locally underlie the basalt flows, consist of brown, yellowish-brown, reddish-brown, and reddish-purple tuff, lapilli tuff, tuff-breccia, and agglomerate. Described in more detail by McAllister (1956), Hall and MacKevett (1962), and Stinson (1977). Probably early Pliocene and latest Miocene in age. K-Ar ages of two basalt flows in the map area are 5.4±0.2 and 4.3±0.5 Ma; K-Ar age of another flow just south of the area is 6.7±0.6 Ma (all K-Ar ages by Larsen, 1979)

Tf **Fanglomerate (Tertiary)**—Firmly consolidated deposits of locally derived gravel and sand that demonstrably underlie Tertiary basalt (unit Tb). Mapped only on west side of the Inyo Mountains, where the deposits typically have a distinctive grayish-yellow to yellowish-orange color. Maximum exposed thickness about 40 m (Swanson, 1996). Probably correlative with deposits in the lower part of unit QTa, and also with deposits of the Coso Formation that predate latest Miocene (~5.5 to 6 Ma) volcanic rocks in the Coso Range, 3 to 15 km south of the map area (Bacon and others, 1982)

## INTRUSIVE ROCKS AND VEINS

q **Quartz veins (Cenozoic or Mesozoic)**—Veins cutting Mississippian rocks near Cerro Gordo Mine. Unit includes Castle Rock vein of Merriam (1963)

KJg **Leucocratic granite (Cretaceous or Jura**ssic)—Light-colored, medium-grained biotite granite. Forms small masses in western part of map area

KJdi **Diorite (Cretaceous or Jurassic)**—Biotite-hornblende diorite spatially associated with leucocratic granite (KJg)

KJf **Younger felsite intrusions (Early Cretaceous or Late Jurassic)**—Light-colored, aphanitic to very fine grained intrusions, primarily dikes, composed of microcrystalline feldspar, quartz, and minor muscovite; locally spherulitic. Locally cuts dark-colored dikes (Jd). One dike in map area has a U-Pb (zircon) minimum age of about 140 Ma (Dunne and Walker, 1993; Stone and others, 2004)

Jd **Dark-colored dikes (Late Jurassic?)**—Dark-gray, greenish-gray, and reddish-brown, porphyritic dikes, probably of dioritic composition. Composed of 10 to 50 percent plagioclase, hornblende, and pyroxene phenocrysts mostly 1 to 3 mm long in a microcrystalline groundmass. Both phenocrysts and groundmass are altered. Dikes are mostly 1 to 5 m wide; a few are as much as 50 to 100 m wide. Undated in map area, but provisionally considered part of the regionally extensive Independence dike swarm of Late Jurassic age

Jdv **Deformed intrusions of variable composition (Late to Middle Jurassic?)**—Light-gray to greenish-gray, aphanitic to medium-grained porphyritic intrusive masses of intermediate to mafic composition. May incorporate more than one suite of intrusions. Commonly deformed by boudinage, cleavage, and shearing (Swanson, 1996)

Jmh **Mafic hypabyssal intrusion (Late to Middle Jurassic?)**—Large, discordant mass intrusive into lower and middle parts of the Inyo Mountains Volcanic Complex

Jad **Altered diorite (Late to Middle Jurassic?)**—Variably sheared greenish-gray to reddish-brown, medium- to very fine grained hornblende(?)-biotite diorite and quartz diorite. Moderately to intensely altered to mixtures of white mica, chlorite, iron oxides, and hydroxides

Jh **Hunter Mountain Quartz Monzonite (Middle to Early Jurassic)**—Medium- to coarse-grained quartz monzonite. Typically contains 25 to 45 percent orthoclase, 35 to 55 percent plagioclase, 10 to 20 percent quartz, 3 to 20 percent mafic minerals (primarily hornblende), and accessory magnetite and sphene (McAllister, 1956). Part of composite Hunter Mountain Batholith, which Dunne and others (1978) reported to have an age range of about 167 to 185 Ma

Jf **Older felsite intrusions (Jurassic?)**—Light-colored, aphanitic to fine-grained felsite. Composed of microcrystalline to fine-grained feldspar and rare to abundant quartz; plagioclase phenocrysts 0.5 to 3 mm long are present locally. Primarily forms sills as wide as 230 m, but also forms discordant plutons

Ji **Altered fine-grained intrusions (Jurassic?)**—Brown to brownish-orange, highly altered and weathered intrusive rocks. Aphanitic to fine-grained; composed of sericitized plagioclase, altered pyroxene or hornblende, quartz, and abundant opaque minerals; contains phenocrysts less than 2 mm in diameter. Original composition probably dioritic

Jmp **Hornblende monzodiorite to monzonite porphyry (Jurassic?)**—Quartz-poor porphyritic rocks that form discordant intrusions near the Cerro Gordo Mine. Composed of about 80 percent phenocrysts 1 to 10 mm long in a dark, fine-grained groundmass of potassium feldspar, hornblende, minor quartz, and alteration minerals. Phenocrysts are dominantly plagioclase, less abundant hornblende, and rare pink potassium feldspar. Overall composition is 50 to 70 percent plagioclase, 10 to 35 percent potassium feldspar, 15 to 25 percent hornblende, and less than 5 percent quartz (Stone and others, 2004)

## SEDIMENTARY AND VOLCANIC ROCKS

Jiv **Inyo Mountains Volcanic Complex (Jurassic)**—Lithologically heterogeneous volcanic and volcanogenic sedimentary rocks (Merriam, 1963; Dunne and Walker, 1993; Dunne and others, 1998; Stone and others, 2004). Undivided where exposed in narrow fault slivers. Elsewhere, divided into the following subunits:

Jivu **Upper part (Late and Middle Jurassic)**—Volcanogenic sandstone, siltstone, and conglomerate; rare calcareous strata; and welded tuff and lava flows. Thickness about 400 m with top not exposed

Jivm **Middle part (Middle Jurassic)**—Silicic crystal-lithic welded ash-flow tuff; less abundant andesite and rhyolite lava flows; and subordinate volcanogenic sandstone and conglomerate. Thickness about 300 m

Jivl **Lower part (Middle or Early Jurassic?)**—Volcanogenic sandstone, conglomerate and breccia in laterally variable proportions; less abundant basaltic lava flows; and rare felsic tuff. Stratigraphic relations at base of unit generally obscured along faulted contact with the Union Wash Formation. Thickness about 450 m. Unit includes:

cg **Basal conglomeratic unit**—Conglomeratic rocks as much as 80 m thick containing mostly limestone clasts in the lower part and mostly volcanic-rock clasts in the upper part

**Union Wash Formation (Middle? and Early Triassic)**—Fine-grained marine sedimentary rocks that include shale, siltstone, sandstone, and limestone (Stone and others, 1991, 2004). Equivalent to unnamed Triassic strata of Merriam (1963) and Stone and others (1989). Divided into the following members:

**Upper member (Middle? and Early Triassic)**—Divided into the following subunits:

ŦRuu4 **Subunit 4**—Consists primarily of brown- to yellowish-brown, thin-bedded quartzose siltstone and shale. Upper part contains limestone and dolomite. Thickness 200 to 300 m. Unit includes:

ls **Limestone**—Medium- to dark-gray, micritic and locally oolitic limestone. Forms a bed 4 to 20 m thick that locally is structurally repeated by folding and faulting

ŦRuu3 **Subunit 3**—Dark-gray, ledge-forming micritic limestone. Forms planar beds 1 to 5 cm thick separated by thin partings of light-brown siltstone or mudstone. Thickness 75 to 95 m

ŦRuu2 **Subunit 2**—Gray, purplish-gray, brownish-gray, and brown quartzose siltstone to very fine grained sandstone and light- to medium-gray limestone; basal 10 m consists of yellow shale. Thickness 80 to 100 m

ŦRuu1 **Subunit 1**—Dark-gray micritic limestone; forms massive ledge. Average thickness about 10 m

ŦRum **Middle member (Early Triassic)**—Yellow shale and medium-gray, thin-bedded micritic limestone. Most parts of member consist primarily of shale and widely spaced limestone interbeds; includes a few limestone-dominated intervals as much as 25 m thick. Uppermost 40 to 50 m is a marker zone of bright yellowish-brown shale. Thickness 200 to 300 m

ŦRul **Lower member (Early Triassic)**—Gray to brown, silty to sandy limestone and calcareous siltstone to fine-grained sandstone. Characterized by thin, planar to wavy bedding, distinctive nodular texture, and local presence of minute black gastropod casts. Forms resistant crags and hogbacks. Thickness generally 30 to 40 m. Locally includes:

ŦRuls **Basal sandstone unit**—Yellowish-gray, fine-grained, calcareous sandstone and siltstone, and subordinate dark-gray mudstone. Maximum thickness about 40 m

**Owens Valley Group (Early Triassic to Cisuralian)**—Lithologically diverse marine and nonmarine sedimentary rocks (Merriam and Hall, 1957; Merriam, 1963; Stone and Stevens, 1987; Stone and others, 1989, 2000, 2004). In map area, consists of the following units:

**Conglomerate Mesa Formation (Early Triassic and Lopingian)**—Conglomerate, sandstone, and minor limestone (Stone and Stevens, 1987; Stone and others, 1989, 2000, 2004). In type area, 1 km north of the map area, formation consists of three members (C, B, and A in descending order); Stone and Stevens, 1987; Stone and others, 2000). In map area, only members C and B are recognized:

ŦRcc **Member C (Early Triassic)**—Gray to brown, thick-bedded pebble and cobble conglomerate and subordinate fine- to coarse-grained sandstone. Conglomerate clasts composed of limestone, quartzite, gray chert, and siltstone. Probably nonmarine. Age based on conformable contact with overlying Union Wash Formation (Stone and others, 2000). Thickness 10 to 150 m

Pcb **Member B (Lopingian)**—Light-gray, thick-bedded sandy and pebbly limestone. Forms lenticular exposures along the northern and eastern base of Conglomerate Mesa. Shallow-water marine. Age based on ammonoids, brachiopods, and conodonts in type area (Stone and others, 2000). Maximum thickness in map area about 10 m

ŦRPs **Sandstone and chert-pebble conglomerate (Early Triassic or Permian)**—Unit locally present below rocks mapped as member C of the Conglomerate Mesa Formation (ŦRcc) and above rocks mapped as unit 12b of the sedimentary rocks of Santa Rosa Flat (Ps12b). Probably nonmarine. Maximum thickness about 30 m

Psu **Sedimentary rocks of Santa Rosa Flat (Guadalupian? and Cisuralian)**—Heterogeneous sequence composed of sandstone, siltstone, limestone, limestone conglomerate, and shale (Magginetti and others, 1988; Stone and others, 1989). Present in eastern part of map area. Includes some rocks previously mapped as Bird Spring(?) Formation by McAllister (1956). Mapped as an undivided unit (Psu) in a few small areas that were not studied in detail. Elsewhere, divided into the following subunits:

**Unit 12 (Guadalupian or Cisuralian)**—Composed primarily of fine-grained clastic rocks. Probably nonmarine. Thickness 120 to 300 m. Divided into the following subunits:

Ps12b **Unit 12b**—Yellow shale; yellowish-brown to brown, calcareous siltstone and fine-grained sandstone; minor gray to bluish-gray, pebbly limestone; and rare brown-weathering, chert-pebble conglomerate. Pebbly limestone is lithologically similar to rocks of the locally underlying limestone conglomerate unit (Psc), but limestone clasts are generally smaller. Commonly overlies unit 11 (Ps11); locally overlies unit 12a (Ps12a)

Ps12a **Unit 12a**—Maroon and greenish-gray shale

Ps11 **Unit 11 (Guadalupian or Cisuralian)**—Brown, yellowish-brown, and reddish-gray, fine- to coarse-grained sandstone, siltstone, and subordinate conglomerate. Probably nonmarine. Thickness 200 to 250 m

Psc **Limestone-clast conglomerate (Guadalupian or Cisuralian)**—Medium- to dark-gray, massive conglomerate composed of poorly sorted, tightly to loosely packed, angular to subangular limestone clasts 1 to 20 cm in diameter and rare angular chert pebbles in a matrix of fine-grained, silty limestone. Probably nonmarine. Locally overlies unit 10 (Ps10). Maximum thickness about 60 m

Ps10 **Unit 10 (Guadalupian? and Cisuralian)**—Medium-gray micritic to bioclastic limestone in which marine fossils are locally abundant. Shallow-water marine. Fusulinids suggest a Roadian or Leonardian age (Stevens and Stone, 2009c); brachiopods suggest a Leonardian or younger age (Hall and MacKevett, 1962). Unit also contains bryozoa, gastropods, and corals. Maximum thickness about 40 m

Ps9 **Unit 9 (Cisuralian)**—In southern part of map area, composed primarily of yellow shale. In northern part of area, composed of gray shale, ochre to brown calcareous siltstone to fine-grained sandstone, and minor silty, bioclastic limestone in which fusulinids are locally abundant and corals are sparse. Probably mostly if not entirely marine. Fusulinids indicate a Leonardian age (Magginetti and others, 1988; Stevens and Stone, 2009c). Unit thickness 75 to 300 m. In northern part of area, includes the following subunit:

Ps9s **Predominantly siltstone and fine-grained sandstone**

**Graded limestone unit (Cisuralian)**—Thick, stratigraphically and structurally complex unit primarily characterized by medium- to dark-gray, bioclastic and conglomeratic limestone in beds that range from 5 cm to more than 1 m thick. Graded beds, which suggest deep-water deposition by turbidity currents, predominate. Limestone, which contains abundant echinodermal debris, fusulinids, shell fragments, coral fragments, and bryozoans, is interbedded with variable proportions of maroon, brown, ochre, and gray calcareous mudstone and siltstone. Fusulinids suggest a Leonardian to late Wolfcampian age (Stone, 1984; Stevens and Stone, 2009a). Previously considered part of unit 8 (Stone and others, 1989). Divided into the following subunits:

Psg3 **Subunit 3**—Exposed northeast of Conglomerate Mesa. Predominantly thin-bedded, gray, calcareous mudstone and ochre to brown, calcareous siltstone and fine-grained calcareous sandstone; minor dark-gray, mostly fine grained, graded limestone beds generally less than 30 cm thick. Fusulinids and other bioclasts are present in the coarsest limestone beds. Fusulinids suggest a Leonardian to late Wolfcampian age (Stone, 1984). Depositionally overlies unit 7 (Ps7) on a sharp, but concordant, contact; gradationally overlain by unit 9 (Ps9). Unit thickness uncertain because of faulting, but probably about 425 m

**Subunit 2—**Exposed southeast of Conglomerate Mesa. Structurally overlies unit 6 (Ps6) and subunit 1 of the graded limestone unit (Psg1) on the Malpais Fault;

structurally overlain by unit 9 (Ps9) on another fault. Stratigraphic relation to subunits 1 and 3 (Psg1 and Psg3) is uncertain. Fusulinids suggest a Leonardian age (Stone, 1984). Further divided into the following subunits, which form an apparently concordant depositional sequence estimated to be as much as 2,400 m thick:

Psg2d **Subunit 2d**—Ochre to maroon calcareous mudstone, siltstone, and fine-grained sandstone, interbedded with equally to slightly less abundant graded beds of dark-gray limestone. Fusulinids are present locally in the limestone. Gradationally overlies subunit 2c (Psg2c). Maximum exposed thickness about 600 m

Psg2c **Subunit 2c**—Dark-gray, graded limestone beds. Beds are thick and coarse grained (in part conglomeratic) in lower part of subunit, becoming thinner and finer grained up section. Crinoid debris and intraclasts are abundant; fusulinids and corals are present locally. Gradationally overlies subunit 2b (Psg2b). Estimated thickness about 600 m

Psg2b **Subunit 2b**—Dark-gray, thick-bedded to massive, coarse-grained to conglomeratic limestone; includes some graded beds. Sharply overlies subunit 2a (Psg2a). Estimated thickness about 450 m

Psg2a **Subunit 2a**—Dark-gray, thick, graded bioclastic limestone beds that locally contain fusulinids. Base faulted. Estimated exposed thickness about 750 m

Psg1 **Subunit 1**—Exposed south and southwest of Conglomerate Mesa. Predominantly dark-gray, graded limestone beds typically between 10 and 75 cm thick. Limestone beds are richly bioclastic and commonly contain abundant fusulinids. Matrix-supported limestone-clast conglomerate beds interpreted as submarine debris-flow deposits locally are as much as 7 m thick. Maroon to ochre calcareous siltstone and mudstone are present in varying amounts and are most abundant in the lower part of the subunit. Basal beds of subunit depositionally overlie rocks questionably assigned to unit 6 (Ps6); uppermost beds are stratigraphically overlain by unit 9 (Ps9). Fusulinids suggest that most of unit probably is of late Wolfcampian age; uppermost part is Leonardian (Stone, 1984). Subunit is at least 500 m thick and may be in excess of 1,000 m thick, but disruption by faults precludes an accurate estimate of thickness

Ps8 **Unit 8 (Cisuralian)**—Medium- to dark-gray, fossiliferous limestone, interbedded with subordinate grayish-orange to ochre calcareous siltstone and pink shale. Limestone locally contains abundant fusulinids and sparse corals. Shallow-water marine. Fusulinids suggest a Leonardian age (Magginetti and others, 1988; Stevens and Stone, 2009c). Maximum thickness about 30 m. Excludes most of the rocks previously assigned to unit 8 of Stone and others (1989), which included rocks herein assigned to the graded limestone unit

Ps7 **Unit 7 (Cisuralian)**—Composed primarily of light-gray, massive to thick-bedded, echinodermal limestone that locally contains diverse marine fossils including algae, sponges, fusulinids, brachiopods, bryozoans, corals, and probable hydrozoans (Rigby and others, 2004). Upper part is locally composed of dark-gray limestone that contains abundant brachiopods and is interbedded with tan to pink shale; lower part is locally composed of interbedded limestone and yellowish-brown siltstone. Shallow-water marine. Fusulinids indicate a late Wolfcampian age (Magginetti and others, 1988; Stevens and Stone, 2009c). Thickness 20 to 100 m

Ps6 **Unit 6 (Cisuralian)**—Brown to yellowish-brown, thin- to thick-bedded, very fine to fine-grained sandstone, calcareous sandstone, and siltstone; and medium- to dark-gray, thin- to thick-bedded bioclastic and conglomeratic limestone in which fusulinids and other marine fossils are abundant. Ammonoids are present locally. Several marker beds of bioclastic and conglomeratic limestone (blue line symbol) are mapped; these beds exhibit graded bedding and other features that indicate deep-water deposition by turbidity currents. Fusulinids indicate a late Wolfcampian age (Magginetti and others, 1988). Thickness about 500 m

**Unit 5 (Cisuralian)**—Dark-gray micritic limestone and subordinate brown to yellowish-brown siltstone and pink shale. Thickness about 200 m. Divided into the following subunits:

Ps5l **Predominantly limestone**

Ps5s **Predominantly siltstone and shale**

Ps4 **Unit 4 (Cisuralian)**—Brown to yellowish-brown sandstone, calcareous sandstone, siltstone, and shale; and medium- to dark-gray, thin- to thick-bedded bioclastic and conglomeratic limestone (including marker beds shown by blue line symbol). Graded bedding and Bouma sequences indicate deep-water deposition by turbidity currents. Fusulinids, corals, and other marine fossils are abundant in limestone; the fusulinids indicate a middle Wolfcampian age (Magginetti and others, 1988). Ammonoids are present locally (Magginetti, 1983). Thickness about 600 m. Unit includes:

lcg **Limestone conglomerate**—A thick bed of pink, matrix-supported limestone conglomerate interpreted as a submarine debris-flow deposit. Contains fusulinids and corals

Ps3 **Unit 3 (Cisuralian)**—A single thick, light- to medium-gray bed that grades from bioclastic limestone and limestone conglomerate at the base to fine-grained limestone at the top. Lower part contains abundant fusulinids and scattered coral fragments. About 20 m thick in most places. Fusulinids indicate a middle Wolfcampian age (Magginetti and others, 1988)

Ps2 **Unit 2 (Cisuralian)**—Upper one-third consists of light-gray calcareous siltstone, silty limestone, and, near the top, a few beds of dark-gray calcarenitic limestone; lower two-thirds consists of brown, thick-bedded, very fine grained sandstone and siltstone that forms beds 40 cm to 1 m thick. Calcareous rocks in upper part contain graded bedding and Bouma sequences that indicate deep-water deposition by turbidity currents. Thickness 150 to 250 m. Possibly equivalent to basal clastic unit of the deep-water marine Darwin Canyon Formation (Stone and others, 1987) in Darwin Canyon, 20 km southeast of map area

Ps1 **Unit 1 (Cisuralian)**—Yellowish-brown to brown, thin-bedded calcareous siltstone and shale; subordinate medium- to dark-gray, thin- to thick-bedded bioclastic and conglomeratic limestone. Graded bedding and Bouma sequences indicate deep-water deposition by turbidity currents. Middle Wolfcampian fusulinids and corals locally present in limestone (Magginetti and others, 1988); one bed contains reworked Pennsylvanian fusulinids and conodonts. Ammonoids are present locally. Maximum exposed thickness about 380 m; base covered. Possibly equivalent to the Osborne Canyon Formation (Stone and others, 1987) in Darwin Canyon, 20 km southeast of map area

Pl **Lone Pine Formation (Cisuralian)**—Medium- to dark-gray and yellowish-gray, thin-bedded to laminated calcareous and dolomitic mudstone; thin-bedded calcareous siltstone and very fine to fine-grained sandstone; and scattered thicker beds (20 to 80 cm) of micritic limestone and dolomite (Stone and Stevens, 1987; Swanson, 1996; Stone and others, 2000, 2004; Stevens and others, 2001). Deep-water marine. Present in western part of map area, where maximum exposed thickness is about 1,200 m (Swanson, 1996). Locally includes:

Pll **Limestone**—Medium- to dark-gray, mostly thin-bedded limestone similar to rocks in upper part of Keeler Canyon Formation (PIPku). Thickness about 30 m

PIPa **Argillite and hornfels (Cisuralian and Pennsylvanian?)**—Reddish-brown-weathering, fine-grained, thinly layered argillite and calc-silicate hornfels; minor limestone and marble are present locally. Stratigraphically equivalent to lower part of the Lone Pine Formation (Pl) and upper part of the Keeler Canyon Formation (PIPku) on lower west slope of the Inyo Mountains where these units were intruded and metamorphosed by abundant felsite sills (unit Jf)

**Keeler Canyon Formation (Cisuralian to Early Pennsylvanian)**—Thick unit primarily composed of medium- to dark-gray, evenly bedded limestone interpreted to have been deposited as turbidites (Merriam, 1963; Werner, 1979; Swanson, 1996; Stevens and others, 2001; Stone and others, 1989, 2004). Divided into the following subunits:

PIPku **Upper part (Cisuralian to Middle Pennsylvanian)—**Medium- to dark-gray, evenly bedded, bioclastic limestone and silty to sandy limestone; tan-weathering calcareous siltstone; and gray, tan, and pink calcareous mudstone. Limestone is characterized by graded bedding and other features indicating deep-water deposition by turbidity currents. Thickness as much as 1,260 m. Includes Salt Tram and Cerro Gordo Spring members of Stevens and others (2001), which are dated as Cisuralian to Middle Pennsylvanian based on fusulinids and conodonts. In the northeastern part of the map area, unit includes some rocks previously mapped as part of the Bird Spring(?) Formation by McAllister (1956). In the Santa Rosa Hills, unit consists of rocks previously assigned to the Osborne Canyon Formation by Magginetti and others (1988) and Stone and others (1989). These rocks, which are older than the typical Osborne Canyon Formation, consist of the following units:

PIPkuf **Fine-grained upper unit (Cisuralian and Late Pennsylvanian)—**Predominantly silty to fine-grained sandy limestone and calcareous siltstone to fine-grained sandstone. Minor coarse-grained, bioclastic limestone forms graded beds that indicate deposition by turbidity currents. Rocks near top of unit contain early Cisuralian conodonts (S.M. Ritter, written commun., 2007); rocks near base contain fusulinids considered earliest Permian in age by Magginetti and others (1988), but more recently interpreted as latest Pennsylvanian (Stevens and others, 2001; Stevens and Stone, 2007). Maximum exposed thickness about 250 m; top covered by Quaternary alluvium

IPkuc **Coarse-grained lower unit (Late and Middle? Pennsylvanian)—**Thick-bedded to massive, echinodermal and conglomeratic limestone. Contact with the underlying Tihvipah Member (IPkt) is sharp and probably disconformable. Thickness about 20 to 50 m

IPkt **Tihvipah Member (Middle and Early Pennsylvanian)—**Medium- to dark-gray, thin- to thick-bedded, cherty micritic limestone, silty limestone, and tan-weathering calcareous siltstone. Limestone typically contains spherical to subspherical nodules ("golf balls") of dark-gray chert (Merriam, 1963; Stevens and others, 2001). Includes rare bioclastic beds interpreted as debris-flow deposits that suggest a relatively deep water sedimentary environment. North of Conglomerate Mesa, member contains ammonoids (advanced *Proshumardites* or primitive *Agathiceras*) of probable Middle Pennsylvanian age (B.F. Glenister, written commun., 1975). In the Santa Rosa Hills, the lower part of member (below the lowest "golf-ball" beds) contains brachiopods identified as *Hustedia miseri* Mather of Early Pennsylvanian age (M.A. Wilson, written commun., 1984). In most parts of the map area, unit has a maximum thickness of about 30 m and overlies the Rest Spring Shale (Mr) on the Morning Star Thrust Fault. A depositional contact with the Rest Spring Shale, along which limestone and argillite are interbedded, is locally preserved in the Fishhook hills (lower plate of Fishhook Thrust Fault). In the Santa Rosa Hills, unit is about 60 m thick, conformably overlies the Indian Springs Formation (Mi), and locally includes 10 m of brown- to orange-weathering siltstone at or near the top

Mr **Rest Spring Shale (Late Mississippian)—**Dark-brown to black shale (Merriam, 1963; Stone and others, 1989, 2004). Probably deep-water marine. Locally altered to argillite or hornfels; sheared in places. Contains Late Mississippian (Chesterian) ammonoids northwest of Cerro Gordo Mine (Gordon, 1964; Titus, 2000). In addition, a sample within 10 m of the top of the formation in the Fishhook hills contains brachiopods identified as *Eolissochonetes*? aff. *E*? *pseudoliratus* (Easton) of Late Mississippian age (J.T. Dutro, Jr., written commun., 1986). Thickness 150 to 350 m

Mi **Indian Springs Formation (Late Mississippian)—**Brown-weathering, fine-grained, plane-laminated and cross-laminated quartzite, siltstone, and shale; rare light- to medium-gray, fine-grained limestone (Dunne and others, 1981). Also includes minor phosphate-pebble conglomerate (Miller, 1989), some of which Stone and others (1989) previously considered to be in the lowermost part of the Tihvipah Limestone but which we herein assign to the uppermost part of the Indian Springs Formation. Shallow-water marine. Contains brachiopods identified as *Quadratia* cf. *Q. hirsutiformis* (Walcott) and "*Avonia*" *subsulcata* (Girty)? of Late Mississippian age (M. Gordon, Jr., and T.W. Henry, written commun., 1984). Maximum thickness about 30 m. Contact with the underlying Santa Rosa Hills Limestone (Msr) is sharp and probably disconformable (Miller, 1989)

Mmt **Mexican Spring Formation and Tin Mountain Limestone, undivided (Late and Early Mississippian)**—Structurally complex fault blocks of very fine grained quartzite (Mexican Spring Formation) and subordinate medium- to dark-gray limestone (Tin Mountain Limestone)

Mm **Mexican Spring Formation (Late Mississippian)**—Composed primarily of light-gray, brown-weathering, calcareous quartzose siltstone to very fine grained sandstone (Stevens and others, 1996; Stone and others, 2004). Upper part locally consists of light-gray, very fine grained siltstone. In Fishhook hills, includes a few graded limestone beds interpreted as turbidites (Klingman, 1987). Unit was previously mapped as siltstone member of the Perdido Formation (Stone and others, 1989). Probably deep-water marine. Thickness 40 to 100 m

Msrs **Santa Rosa Hills Limestone and Stone Canyon Limestone, undivided (Late and Early Mississippian)—**Structurally complex limestone outcrops near southeast corner of map area, where detailed mapping has not been conducted

Msr **Santa Rosa Hills Limestone (Late and Early Mississippian)—**Light- to very light gray, thick-bedded, fine- to coarse-grained echinodermal limestone (Dunne and others, 1981; Stone and others, 1989). Colonial corals abundant. Contains sparse nodular gray chert. Shallow-water marine. Thickness 80 to 100 m

Mlr **Leaning Rock Formation (Early Mississippian)**—Dark-gray, thin- to medium-bedded limestone; black, spiculiferous chert; and minor bioclastic beds interpreted as turbidites and debris-flow deposits (Klingman, 1987; Stevens and others, 1996). Deep-water marine. Present only in the Fishhook hills, where exposed thickness is about 30 m and the base is faulted. Previously mapped as limestone member of the Perdido Formation (Stone and others, 1989)

Msc **Stone Canyon Limestone (Early Mississippian)**—Medium- to dark-gray, thin- to medium-bedded, fine-grained limestone, interbedded with abundant brown-weathering siliceous limestone and chert (Stevens and others, 1996). Upper 150 m of unit contains minor echinodermal limestone and locally contains brachiopods, gastropods, and corals (Klingman, 1987). Lower part contains rare graded limestone beds interpreted as turbidites and a pebbly calcareous mudstone bed interpreted as a debris-flow deposit (Klingman, 1987). Chert is particularly abundant in the basal 25 m. Relatively deep water marine. Thickness 450 to 530 m. Previously mapped as limestone member of the Perdido Formation (Stone and others, 1989)

Mt **Tin Mountain Limestone (Early Mississippian)—**Medium- to dark-gray or dark-bluish-gray, thin- to medium-bedded mostly fine grained limestone that locally contains gray to black chert lenses and nodules (Merriam, 1963; Stone and others, 1989, 2004). Some beds contain abundant coarse echinoderm debris. Probably shallow-water marine. Thickness 25 to 180 m

Dl **Lost Burro Formation (Late and Middle Devonian)—**Composed primarily of light- to dark-gray, thick-bedded, fine-grained limestone and marble (Merriam, 1963; Stone and others, 1989, 2004). Commonly forms steep slopes and cliffs. Thick beds typically display fine planar lamination defined by contrasting shades of gray. Characterized by locally abundant stromatoporoids and branching corals (Merriam, 1963). Uppermost few meters locally consist of vitreous light-gray quartzite. Lower part of formation includes variable amounts of light-gray dolomite and light-gray quartzite. Lower contact placed at base of a transitional zone about 30 m thick in which medium-gray limestone is interbedded with light-gray laminated dolomite similar to Hidden Valley Dolomite. Shallow-water marine. Thickness 550 to 700 m

DSh **Hidden Valley Dolomite (Middle? Devonian to early Silurian)—**Very light gray to light-gray, massive, saccharoidal dolomite (Merriam, 1963; Stone and others, 2004). Typically forms irregular, ledgy slopes. Upper part of formation locally contains a discontinuous zone of sandy dolomite and quartzite. Shallow-water marine. Thickness 450 to 580 m

SOes **Ely Springs Dolomite (early Silurian and Late Ordovician)**—Medium- to dark-gray, thick-bedded dolomite characterized by irregular nodules and lenses of dark-gray chert as much as 15 cm long and aligned parallel to bedding (Merriam, 1963; Stone and others, 2004). Dolomite commonly has irregular mottled texture, possibly resulting from bioturbation; locally contains abundant sand-size fossil debris. Shallow-water marine. Thickness 180 to 250 m

Oe **Eureka Quartzite (Middle Ordovician)—**Light-tan to light-gray, vitreous, fine- to medium-grained quartzite (Merriam, 1963; Stone and others, 2004). Present only at north edge of map area; base not exposed

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## Appendix—Cisuralian Ammonoids

In the early 1980s, two authors of this report (C.H. Stevens and P. Stone) and our colleague R.T. Magginetti collected ammonoid fossils from a small number of localities in the Permian sedimentary rocks of Santa Rosa Flat near Conglomerate Mesa in the area of the present study. We sent these fossils to the University of Iowa to be examined by the ammonoid specialist B.F. Glenister. A short time thereafter, a group from the University of Iowa visited the Conglomerate Mesa area and made an additional, larger collection of ammonoids from the same sequence of strata. Glenister (written commun., 1983) reported on the Conglomerate Mesa fauna in preliminary form and Baker (1986) presented a more detailed treatment, including taxonomic descriptions and photographs, as part of her Ph.D. dissertation. A formal publication, however, was not produced, so the existence of these ammonoids is not widely known.

The exact localities of most of the ammonoid collections noted above are uncertain. It is clear, however, that all of the collections are from Cusuralian (lower Permian) strata of units 1–6 of the sedimentary rocks of Santa Rosa Flat. Our data indicate that some specimens are from unit 6, some are from the lower part of unit 4 (Magginetti, 1983), and others probably are from unit 1.

As reported by Baker (1986), the ammonoids under discussion here contain representatives of the following taxa: *Bamyaniceras* sp.; *Akmilleria electraensis* (Plummer and Scott); *Prothalassoceras bostocki* Nassichuk; *Properrinites cumminsi* (White); *Bransonoceras bakeri* Miller and Parizek; *Daubichites fortieri* (Harker and Thorsteinsson); and *Crimites* cf. *C. subkrotowi* Ruzhentsev. According to Baker (1986) these taxa are consistent with an early to middle Permian age.