Correlation of Permian and Triassic deformations in the western Great Basin and eastern Sierra Nevada: Evidence from the northern Inyo Mountains near Tinemaha Reservoir, east-central California

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ABSTRACT

Geologic relationships exposed near Tinemaha Reservoir southeast of Big Pine, east-central California, provide key chronological and structural constraints for linking Permian and Triassic deformational events recognized in the White and Inyo Mountains in the western Great Basin with those in the eastern Sierra Nevada, particularly the Mount Morrison and Saddlebag Lake pendants. Permian to earliest Triassic deformation in the Tinemaha Reservoir area produced a large north- to northwest-trending, east-vergent, originally recumbent syncline (Mule Spring syncline) cut by an overriding thrust (Strange Hill thrust). We correlate this deformation with a middle Permian to earliest Triassic contractional deformation recognized in the southern Inyo Mountains, and with a major episode of folding and thrust faulting in the eastern Sierra Nevada. After a period of tectonic quiescence and marine sedimentation in the Early Triassic, rocks in the Tinemaha Reservoir area were refolded twice, producing distinctive sets of steeply plunging folds. Similar structures in the Mount Morrison pendant that formed prior to intrusion of a 225 ± 16 Ma dike along the Laurel-Convict fault are correlated with those in the Tinemaha Reservoir area. The timing of these folding events may be similar to that of displacement on the Golconda and/or Lundy Canyon thrusts in the Saddlebag Lake pendant.

Close structural and stratigraphic ties suggest that rocks in the northeastern part of the Mount Morrison pendant and Tinemaha Reservoir area, now separated by ~65 km of dextral displacement along the cryptic Tinemaha fault, originally lay adjacent to one another. This offset postdates Triassic folding and is inferred to predate emplacement of the latest Triassic Wheeler Crest Granodiorite, which crops out across the projected fault trace.

Keywords: deformation, Great Basin, Permian–Triassic, Sierra Nevada, tectonics.

INTRODUCTION

The region encompassing the White and Inyo Mountains and eastern Sierra Nevada in east-central California (Fig. 1) has emerged as a key area for the study of middle Paleozoic to middle Mesozoic evolution of the Cordilleran continental margin (Stevens et al., 1997). Rocks and structures exposed in this region reflect the change from a dominantly passive to a dominantly convergent margin between middle Paleozoic and middle Mesozoic time; the most significant tectonism occurred during the Permian and Triassic.

Permian and Triassic tectonic events in the White and Inyo Mountains have been summarized by Stevens et al. (1997), and those in the Sierra Nevada have been discussed by Schweickert and Lahren (1987, 1993) and Stevens and Greene (1999, 2000). In spite of considerable work on dating rocks and structures in both regions, the paucity of clear stratigraphic and structural ties has made it difficult to evaluate possible correlations of tectonic events.

Rocks in the vicinity of Tinemaha Reservoir at the western foot of the northern Inyo Mountains in Owens Valley (Fig. 1), however, appear to provide such ties. In this area we have identified or reinterpreted critical rocks and structures that can be employed for correlation of tectonic events represented in the White and Inyo Mountains with those in the eastern Sierra Nevada. The purpose of this paper is to show the evidence for these proposed stratigraphic and structural correlations and to use them as a basis for a regional chronology of deformational events that affected the southern part of the North American continental margin during Permian and Triassic time.

OVERVIEW

The primary area of this study includes the basal slopes of the Inyo Mountains east of Tinemaha Reservoir and a few isolated hills west of the mountain front (Fig. 2). The geology of this area, first mapped by Nelson (1966), was later remapped and reinterpreted by Olson (1970) and Stevens and Olson (1972). The geology shown in Figure 2 is modified from Stevens and Olson (1972) on the basis of our more recent mapping. Major differences between this and previously published maps are due to the facts that (1) the structure is very complex, (2) some of the rocks (especially the cherts) retain little of their original structure, and (3) until recently, the ages of several units had been misinterpreted.

Outcrops of particular importance underlie the informally named ''Big Hill'' along the mountain front and ''Strange Hill,'' which is separated from the mountain front by Quaternary alluvium (Fig. 2). An interpretative cross section through these two hills is shown in Figure 3.

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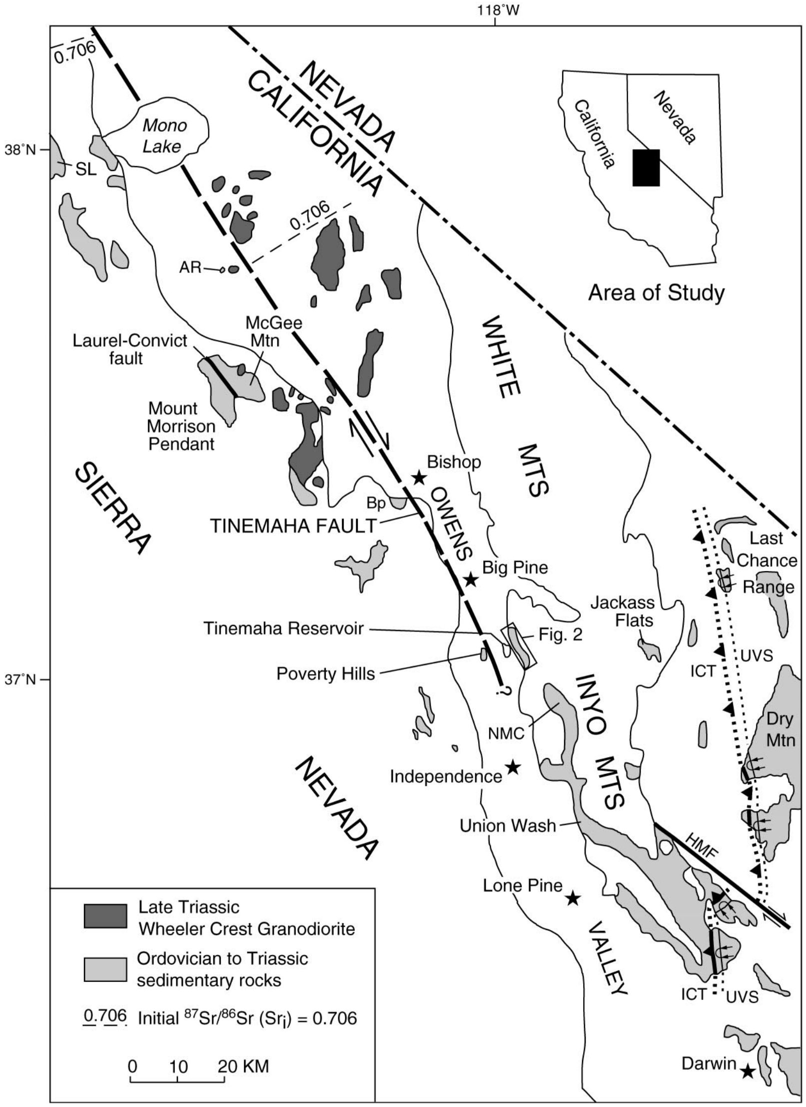

Figure 1. Map showing location of the Tinemaha Reservoir area and other places mentioned in the text. AR—Arcularius Ranch, Bp—pendant southwest of Bishop, HMF—Hunter Mountain fault, ICT—Inyo Crest thrust, NMC—northern Mazourka Canyon, SL—Saddlebag Lake, UVS—Upland Valley syncline. Geology after Jennings (1977).

All the rocks of interest along the base of the mountains west of a high-angle range-front fault are separated into two structural plates by the Big Hill fault (Fig. 3). This low-angle fault is continuously exposed for a distance of several kilometers, and remnants of its upper plate overlie the eastern limb of a major syncline, here called the Mule Spring syncline. The partially overturned western limb of this syncline, in turn, is cut by a fault, here called the Strange Hill thrust (Figs. 2, 3, 4). The complex geology of Strange Hill (Figs. 4, 5) is highly significant for the interpretations made here and therefore was mapped in greater detail than other parts of the area.

STRATIGRAPHY

The stratigraphy of the Tinemaha Reservoir area (Table 1) can be pieced together from several isolated outcrops. The upper plate of the Big Hill fault (Figs. 2, 3) comprises a west-dipping sequence of Cambrian to Silurian rocks. The lower plate of the Big Hill fault contains Devonian separated from Mississippian and Pennsylvanian rocks by the Strange Hill thrust, which is overlapped by Lower Triassic rocks.

Most of the units recognized in the Tinemaha Reservoir area are similar to those exposed farther south in northern Mazourka Canyon (Fig. 1) (e.g., Ross, 1965); these and other units exposed in the area are described briefly in Table 1. Four units, the Ely Springs Dolomite, Mount Morrison Sandstone, Squares Tunnel Formation, and Union Wash Formation are of particular stratigraphic and structural significance and therefore are described here in greater detail.

Ely Springs Dolomite (Ordovician–Silurian)

The Ely Springs Dolomite consists primarily of dark gray chert and chert breccia, with relatively minor dolomite. On Big Hill, where the section is most complete, the formation is divided into three members (Table 1): a lower member composed primarily of thin-bedded, medium to dark gray chert alternating with medium to dark gray dolomite; a middle member consisting of light gray, fine-grained dolomite; and an upper member consisting of thinly bedded, dark gray chert, much of which is highly brecciated. The two lower members bear a general lithologic similarity to exposures of Ely Springs Dolomite in Mazourka Canyon. The upper member, however, differs from rocks assigned to the Ely Springs Dolomite elsewhere in the Inyo Mountains in consisting largely of chert breccia having a jigsaw fabric with a matrix formed of comminuted chert clasts and earlier voids now filled with coarse-grained quartz (Haughy et al., 2000). The chert that forms the breccia apparently was deposited as part of the Ely Springs Dolomite in Ordovician to Early Silurian time, but the age and origin of the brecciation have been uncertain. In northern Mazourka Canyon (Fig. 1), ~13 km southeast of Tinemaha Reservoir, on the other hand, the highest part of the Ely Springs Dolomite consists of moderately disturbed, thin-bedded black chert ~10 m thick, similar to, but not as highly disturbed as, the brecciated chert near Tinemaha Reservoir. This thin-bedded chert unit is not present at the top of the very thin Ely Springs Dolomite 4–5 km farther northwest. We speculate that the brecciated chert in the Tinemaha Reservoir area was originally deposited between Mazourka Canyon and Tinemaha Reservoir and that sometime after lithification (probably in the Silurian) these rocks became unstable and were transported downslope (northwestward) in the form of rockslides and rock avalanches to pile up to a thickness of at least 300 m at the base of a slope near Tinemaha Reservoir.

A chert breccia identical in composition and fabric to the upper member of the Ely Springs Dolomite overlies yellow shale of the Triassic Union Wash Formation near the summit of

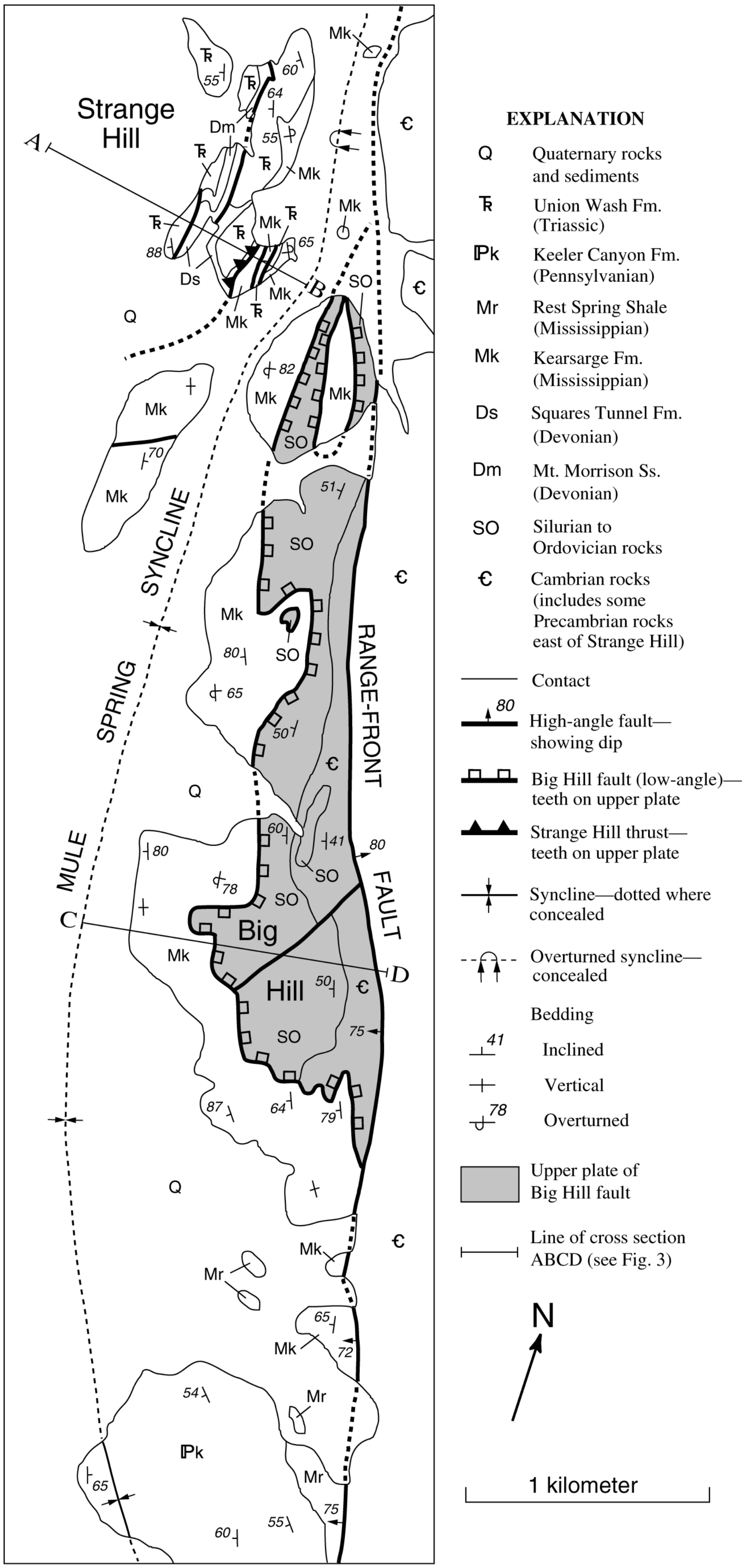

Figure 2. Generalized geologic map of the Tinemaha Reservoir area modified from Stevens and Olson (1972).

Strange Hill (Figs. 4, 5). This chert breccia previously was mapped as a thrust klippe of Ely Springs Dolomite (Olson, 1970; Stevens and Olson, 1972). Here it is reinterpreted as part of the Union Wash Formation because dikes of yellow sedimentary rock extend upward into it from the underlying yellow shale. This breccia is interpreted as a Lower Triassic slide block derived from the previously brecciated upper member of the Ely Springs Dolomite.

Mount Morrison Sandstone and Squares Tunnel Formation (Devonian)

Rocks of Devonian age, not recognized in the Tinemaha Reservoir area until recently (Stevens and Greene, 1999), consist of an overturned, lithologically distinct sequence of pebbly limestone, sandy conglomerate, and phosphatic chert herein assigned to the upper Middle Devonian Mount Morrison Sandstone and Upper Devonian Squares Tunnel Formation. The base of this sequence is not exposed in the Tinemaha Reservoir area, and the top of the sequence is faulted; therefore, the stratigraphic context is unknown. These rocks, however, which are confined to the upper plate of the Strange Hill thrust, provide critical evidence for structural interpretations of the Tinemaha Reservoir area.

Rocks assigned to the Mount Morrison Sandstone at Strange Hill have an aggregate exposed thickness of 25–30 m (Table 1). The lowest beds consist of pebbly limestone turbidites that have yielded late Middle Devonian (Givetian) conodonts. This age is compatible with the probable age of the lower part of the Mount Morrison Sandstone in the Mount Morrison pendant (Stevens and Greene, 1999). The upper 11–14 m consists of conglomerate containing dark gray chert clasts and fragments of several types of Devonian tabulate corals in a matrix of coarse-grained quartz sandstone. This unit is lithologically identical to a conglomerate in the lower part of the Mount Morrison Sandstone at McGee Mountain in the eastern Sierra Nevada (Fig. 1), the only other area where the conglomeratic facies of this formation is known (Stevens and Greene, 1999).

The Mount Morrison Sandstone has been interpreted to represent a major submarine-fan complex derived from the shelf in the eastern Inyo Mountains during the Middle Devonian

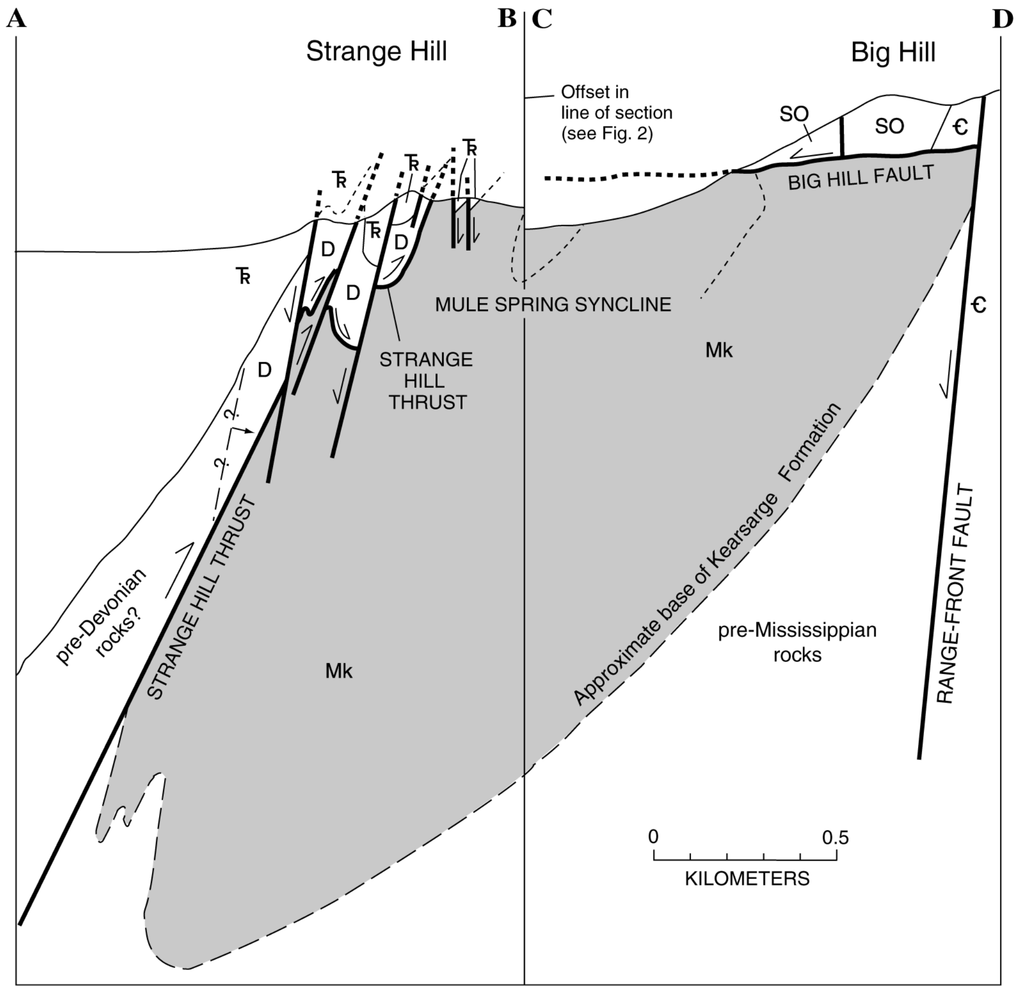

Figure 3. Interpretive cross section drawn across the southern parts of Strange Hill and Big Hill (see Fig. 2 for locations of sections). Map symbols as in Figure 2 except D (Devonian), which includes both Squares Tunnel Formation and Mount Morrison Sandstone. Quaternary deposits not shown. Short-dashed lines represent bedding within Mk and D; arrows indicate facing direction.

(Stevens and Greene, 1999). Exposures of the conglomeratic facies of the Mount Morrison Formation at McGee Mountain, where it fills a channel cut deeply into older rocks, and at Strange Hill are considered to represent the same major feeder channel to that submarine fan (Stevens and Greene, 1999) because of their unique sedimentologic and lithologic similarities.

The Squares Tunnel Formation at Strange Hill consists primarily of thin-bedded to laminated black chert and shale, some with light gray phosphatic blebs and lenses. These rocks concordantly overlie the Mount Morrison Sandstone and closely resemble the Upper Devonian Squares Tunnel Formation in (1) the northern Mazourka Canyon area, where it overlies either the Silurian to Lower Devonian Sunday Canyon Formation of Ross (1966) or the Ely Springs Dolomite, and (2) the eastern Sierra Nevada, where it overlies the Mount Morrison Sandstone (Stevens and Greene, 1999).

Union Wash Formation (Triassic)

The Union Wash Formation, exposed only at Strange Hill (Figs. 3, 5), consists of a basal chert-clast conglomerate overlain by yellow shale and bluish-gray limestone. These rocks, which are structurally complex, contain only rare reworked fossils, and unconformably overlie Devonian and Mississippian rocks, were previously mapped as Pennsylvanian and Permian units (e.g., Nelson, 1966; Stevens and Olson, 1972).

This unit is assigned to the Union Wash Formation because it is similar to that formation exposed in the southernmost Inyo Mountains and near Darwin (Fig. 1). There, conglomerates composed of locally derived clasts are common at the base of the unit (Stone and Stevens, 1988; Stone et al., 1989). Overlying the basal conglomerates both there and in the Tinemaha Reservoir area is yellow shale interbedded with fine-grained, pure, bluish-gray limestone. Especially diagnostic is a thick succession of dark bluish-gray, very fine grained, thin-bedded limestone containing abundant lenticular nodules of black chert exposed on the hill west of Strange Hill. These rocks are lithologically identical to subunit 1 of the upper member of the Union Wash Formation in the Darwin area (Stone et al., 1991) and are dissimilar to any other unit known in the region. These lithologic comparisons leave little doubt that this sequence of rocks does, in fact, represent the Union Wash Formation.

Evidently, the Ely Springs Dolomite cropped out in the immediate area during Early Triassic time. The chert breccia at the summit of Strange Hill, herein included in the Union Wash Formation as previously noted, is

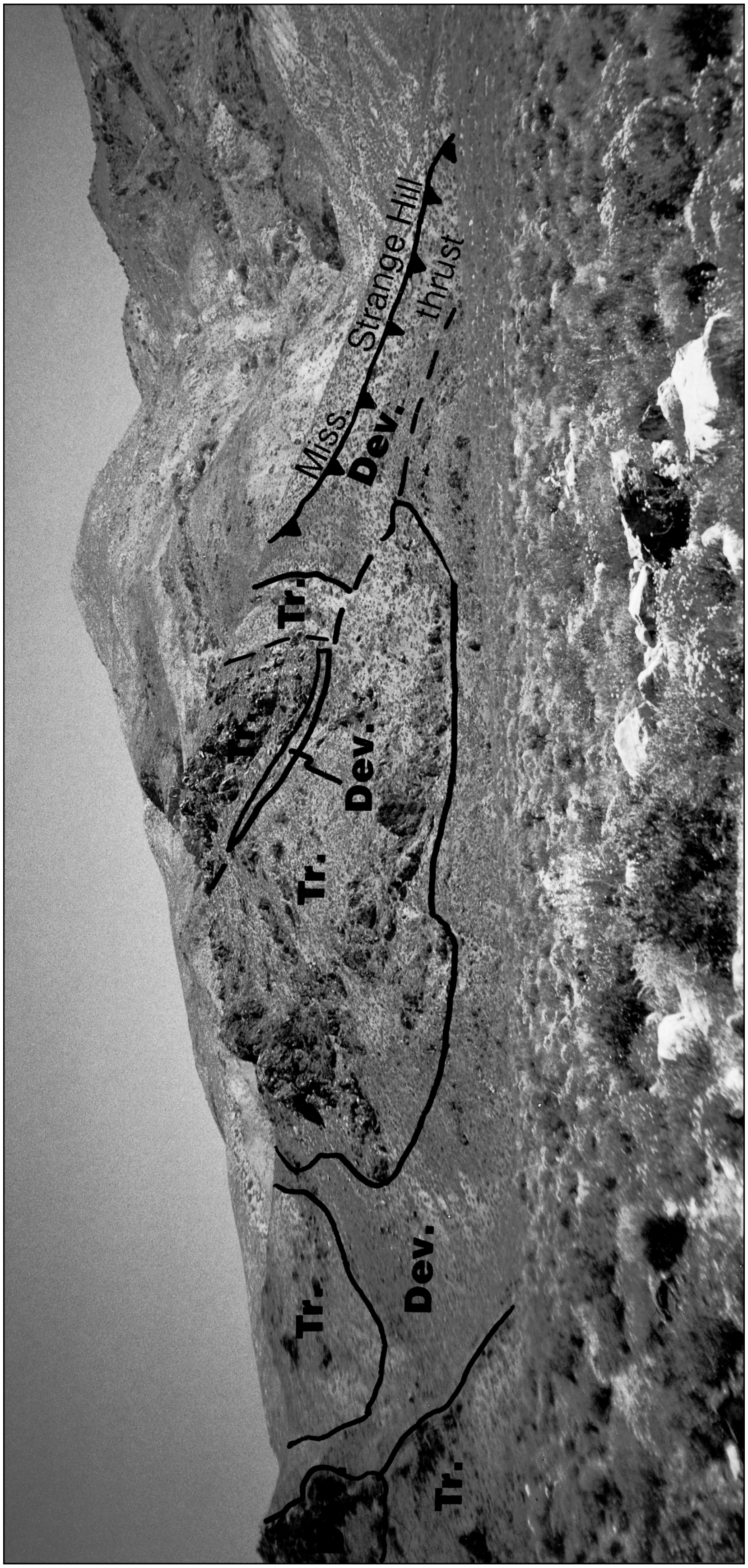

Figure 4. Photograph of the south side of Strange Hill showing the major geologic features. Dev—Devonian rock, Miss—Kearsarge Formation, Tr—Union Wash Formation. Strange Hill thrust is marked with standard thrust symbols.

identical to the rocks of the upper member of the Ely Springs Dolomite exposed along the base of the Inyo Mountains, as are clasts in conglomerates near the base of the Union Wash Formation. In addition, the only fossils recovered from the Union Wash Formation in the area of this study include the conodont *Walliserodus* of Middle Ordovician to Silurian age (Bruce Wardlaw, 1998, personal commun.), a fossil almost surely reworked from the Ely Springs Dolomite.

The unconformity at the base of the Union Wash Formation is exposed in several places. On the west side of Strange Hill, upright beds of the Union Wash Formation unconformably overlie the inverted Mount Morrison Sandstone (Fig. 5). On the south side of the hill, the basal conglomerate of the Union Wash Formation overlies the inverted Squares Tunnel Formation. On the northeastern part of Strange Hill, a massive chert, thought to represent the thoroughly altered basal conglomerate of the Union Wash Formation, is overlain by yellow shale and fine-grained bluish-gray limestone, typical of that formation. This chert overlies Mississippian rocks (Fig. 5), but although the contact is well exposed, its nature is not certain. Because there is no evidence of faulting along the contact, and because the unconformity at the base of the Union Wash Formation cuts uniformly across the stratigraphic section and structures in the previously deformed rocks on Strange Hill, as shown in Figures 5 and 6, we interpret this contact as depositional. Similarly, we interpret the contact between Mississippian rocks and massive chert on the southeastern side of Strange Hill (Fig. 5) as depositional.

The Union Wash Formation is of Early and Middle(?) Triassic age and therefore is approximately coeval with the Candelaria Formation (Speed, 1984), which has been recognized in the Saddlebag Lake pendant (Fig. 1) in the eastern Sierra Nevada by Schweickert and Lahren (1987). The Candelaria Formation is distinct from the Union Wash Formation, however, in lacking limestone and, in the upper part, containing volcanic and granitic clasts indicating a very different provenance.

STRUCTURAL GEOLOGY

The structure of the Tinemaha Reservoir area has been problematic and controversial. Olson (1970), Stevens and Olson (1972), and Stevens (1978) interpreted the dominant structures in the area as a product of regionally significant Mesozoic thrust faulting, whereas Dunne and Gulliver (1978), in keeping with the earlier mapping of Nelson (1966), considered the same structures

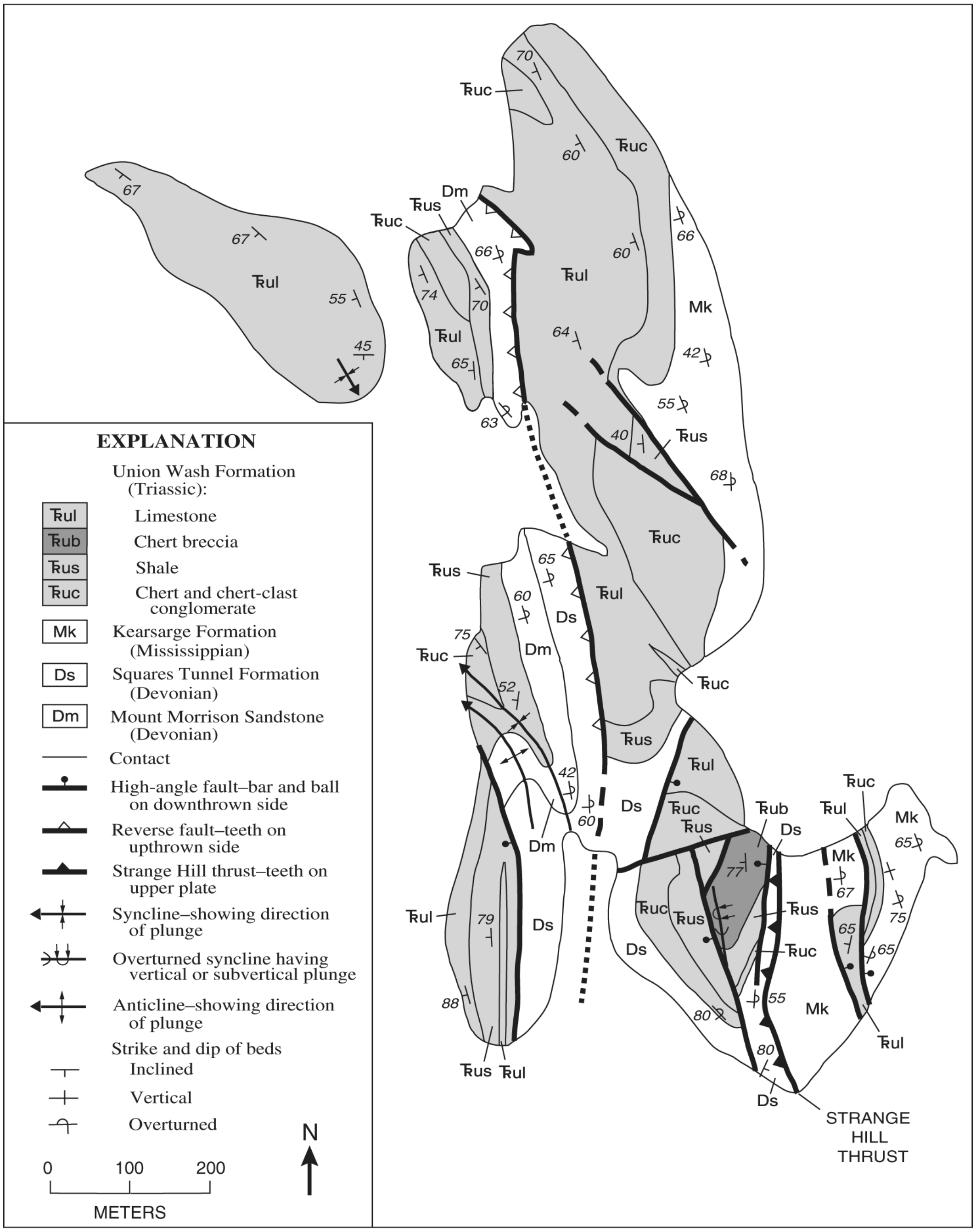

Figure 5. Geologic sketch map of Strange Hill. Truc includes both chert-pebble conglomerate and massive chert of uncertain origin.

to be a product of Cenozoic normal faulting along the front of the Inyo Mountains. The present study has led to a reinterpretation of the structural framework of the Tinemaha Reservoir area, largely on the basis of the improved knowledge of the stratigraphy.

Big Hill and Range-Front Faults

The low-angle Big Hill fault (Figs. 2, 3) and a high-angle range-front fault east of Tinemaha Reservoir have been mapped and interpreted in several different ways. Nelson (1966) mapped the range-front fault as a simple, steeply west-dipping normal fault. Olson (1970), and later Stevens (1978) and Corbett (1989), interpreted the Big Hill fault as part of a regionally significant, east-vergent Mesozoic thrust fault (Inyo thrust) underlying most of the northern Inyo Mountains and emerging on the east side of the range at Jackass Flats (Fig. 1) as the Last Chance thrust of Stewart et al. (1966). Dunne and Gulliver (1978) reinterpreted the Inyo thrust and range-front fault as a zone of Cenozoic extensional faults, which together with associated westward-emplaced slide masses, resulted in a jumble of down-dropped blocks. It now seems clear that the Big Hill fault is a low-angle normal fault and that the high-angle range-front fault cuts it as shown in

TABLE 1. STRATIGRAPHY OF THE TINEMAHA RESERVOIR AREA

System	Series*	Formation	Member	Lithology	Thickness (m)
Overlap assemblage at Strange Hill					
Triassic		Union Wash Formation	upper	Limestone, bluish gray, very fine grained, pure, in beds about 3 cm thick, with abundant, lenticular, black chert nodules	125+
			middle	Shale, yellow to light brown, with local chert-slab conglomerate	20±
			lower	Conglomerate composed of medium to dark gray chert slabs as much as 3 cm thick and 10 cm long	0–3
Poverty Hills					
Permian(?)				Metasiltstone, light gray on fresh surfaces, weathers medium brown; many beds 12–30 cm thick, internally laminated, with interbeds of light gray weathering calc-silicate rock in beds 10–30 cm thick	Undet.
Pennsylvanian	Virgilian (Stevens and Greene, 1999)			Siltstone and calc-silicate hornfels, light brown, laminated, with a 2-m-thick interbed of medium gray, normally graded limestone	Undet.
Lower plate of Big Hill fault					
Pennsylvanian		Keeler Canyon Formation	upper	Siltstone, mudstone, and debris-flow beds, pink and light brown, calcareous	30+
	Atokan (Garlow, 1984; Stevens, unpub.)		middle	Limestone, medium bluish gray, fine grained, with black chert nodules ("golf balls")	30±
	Morrowan (Stone, 1984)		lower	Limestone, medium gray, in turbidite beds as much as 3 m thick, interbedded with subordinate black shale, fine-grained, medium gray limestone, and tan-weathering siltstone	400±
Mississippian		Rest Spring Shale		Shale, black	~300?
	Meramecian (Stevens et al., 1996)	Kearsarge Formation		Mudstone, dark gray, pebbly, with black shale and subordinate dark gray, normally graded calcarenite. In central part of area, includes a thick channel fill composed of resistant calcarenite, conglomerate, and platy siltstone	~1000?
Upper plate of Strange Hill thrust					
Devonian		Squares Tunnel Formation		Chert, black, in beds 2–6 cm thick, containing light-gray, phosphatic blebs and lenses commonly 1 cm thick and 8 cm long; separated by laminae or beds of black shale as much as 5 cm thick	50+
		Mount Morrison Sandstone	upper	Conglomerate formed of clasts and slabs of black and brown chert as much as 30 cm across and 4 cm thick in a matrix of coarse-grained quartz sandstone	11–14
			middle	Chert and argillite, black	8
	Givetian (Stevens and Greene, 1999)		lower	Limestone, medium gray, with pebbles of black chert and argillite; grades upward into poorly sorted conglomerate composed of black chert clasts in a pelmatozoan-rich limestone matrix	6
Upper plate of Big Hill fault					
Silurian		Ely Springs Dolomite	upper	Chert, thin-bedded, dark gray, and chert breccia with jigsaw structure	300+
			middle	Dolomite, light gray, fine grained	25±
Ordovician			lower	Chert, medium to dark gray, alternating with medium- to dark gray dolomite in beds 15–25 cm thick	180±
		Barrel Spring Formation		Shale, medium brown	2.5
		Badger Flat Limestone		Limestone, medium gray, laminated, interbedded with laminae of orange-weathering siltstone containing limestone eyelets and with some micritic limestone beds 2–4 cm thick	100±
		Al Rose Formation		Argillite, orange weathering, locally with distinctive eyes produced by weathering out of limestone lenses. Disrupted by faulting	130±
Cambrian		Tamarack Canyon Dolomite		Dolomite, fine grained, composed of medium to dark gray interbeds. Only small faulted outcrops are present in study area	300±

Note: Undet.—Undetermined; unpub.—unpublished data.
*Based on local fossil occurrences.

Figures 2 and 3. This reinterpretation of the Big Hill fault is based on the geometry of the two plates and the lack of evidence of ductile deformation along the fault surface. The range-front fault is steep and, as pointed out by Dunne and Gulliver (1978), evidently cuts the Big Hill fault where the two faults intersect. This interpretation does not require any fault in the area to underlie the Inyo Mountains as once thought.

Structure of Strange Hill

Our work indicates that the Paleozoic sequence on Strange Hill includes an inverted section of Devonian rocks that has been em-

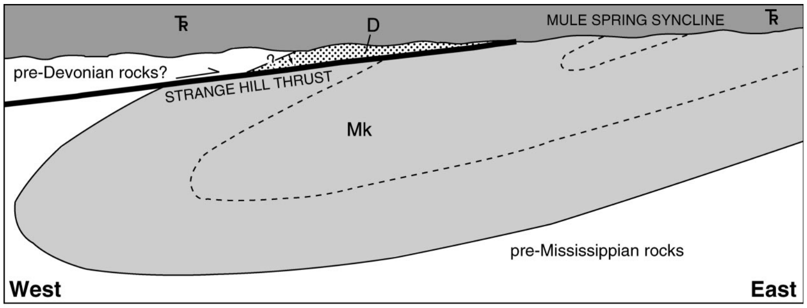

Figure 6. Diagrammatic cross section showing the shape of the Mule Spring syncline and Strange Hill thrust prior to deposition of the Triassic Union Wash Formation. Symbols as in Figure 3.

placed above overturned Mississippian rocks on the Strange Hill thrust. All of these Paleozoic rocks in turn are unconformably overlain by the Lower to Middle(?) Triassic Union Wash Formation. In addition, all rocks on Strange Hill are folded at several different scales. Two large synclines, both involving Devonian and Triassic rocks, have fold widths of at least 100–200 m. One of these, which trends about N10°W, plunges subvertically, opens northward, and is exposed at the southern end of Strange Hill; the other, which trends about N30°W and plunges 40° to 50°NW, is exposed on the west side of the hill and is paired with an anticline on its southwest flank (Fig. 5). On the isolated hill northwest of Strange Hill, a syncline several meters across trends S30°E and plunges ~10°SE. On the southeastern part of Strange Hill, smaller, subvertically plunging folds having wavelengths ranging from centimeters to meters are present in both the Mississippian Kearsarge and Triassic Union Wash formations, showing that the two units were deformed together. Axial planes of most of these small folds dip very steeply. An equal-area stereonet plot of fold hinge lines on Strange Hill and the next hill to the west (Fig. 7A) shows that these fold hinge lines are dispersed along a subvertical plane striking about N28°W. We interpret this pattern to suggest a sequence of two folding events involving rocks as young as Triassic; one of these events produced northwest-trending folds and the other produced northeast-trending folds. At present we have no data to determine which fold set is the older.

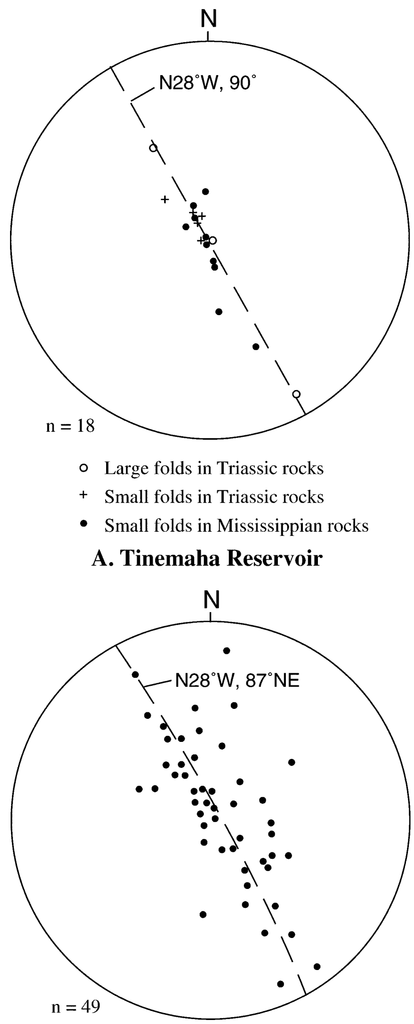

Figure 7. Equal-area stereo plots of fold hinge lines in (A) the Strange Hill area near Tinemaha Reservoir and (B) on the northeast side of the Laurel-Convict fault in the Mount Morrison pendant (from Wise, 1996).

A prominent subvertical cleavage striking about N25°W cuts Mississippian rocks throughout the area; on Strange Hill this cleavage also cuts the Triassic rocks and the Strange Hill thrust. This cleavage apparently is axial planar to the post-Triassic, northwest-trending folds and clearly postdates all the rocks on Strange Hill as well as the Strange Hill thrust.

Strange Hill Thrust

The Strange Hill thrust separates the overturned Devonian rocks of the Mount Morrison Sandstone and Squares Tunnel Formation from overturned Mississippian rocks, mostly assignable to the Kearsarge Formation (Fig. 5). We here interpret this contact to be a fault rather than an overturned depositional contact because (1) the Devonian rocks comprise a stratigraphic sequence unknown elsewhere in the Inyo Mountains, (2) chert-pebble conglomerate like that which characterizes the lowest exposed part of the Mississippian section south of Big Hill and the base of the section in northern Mazourka Canyon is missing, and (3) different Mississippian facies are in contact with the Devonian rocks at different places on Strange Hill. For instance, along the northern part of the contact, Mississippian argillite with thin limestone interbeds (Kearsarge Formation) is present, whereas to the south, a thick black shale (possibly an outcrop of Rest Spring Shale) is present at the contact.

The amount of displacement on the Strange Hill thrust is unknown. The stratigraphic throw is small, but a moderate to a rather large amount of displacement is implied by the presence of units typical of the Sierra Nevada in the upper plate.

Mule Spring Syncline

Recent mapping demonstrates the existence of a major syncline in the Tinemaha Reservoir area (Figs. 2, 3) largely covered by Quaternary alluvium. It is revealed by opposing facing directions in outcrops of the Mississippian Kearsarge Formation between the Inyo Mountains front and the hills to the west and by a synclinal axis exposed in the Keeler Canyon Formation near the southern margin of the area (Fig. 2). Dips in both limbs of the structure generally are steep, and some are overturned. Beds in the east limb may have been overturned during emplacement of the upper plate of the Big Hill fault. The trough of the syncline exposed in the southern part of the area (Fig. 2) is inferred to bend northward, passing between Strange Hill and the base of the Inyo Mountains to the east. The inverted, east-facing Mississippian rocks exposed on Strange Hill are interpreted to lie in the western limb of the Mule Spring syncline, which appears much thinner than the generally upright eastern limb (Figs. 3, 6).

The Mule Spring syncline formed after deposition of the Keeler Canyon Formation and prior to accumulation of the Lower to Middle(?) Triassic Union Wash Formation. Restoration of the Union Wash Formation to horizontal indicates that the syncline was originally recumbent (Fig. 6).

Summary of Deformational History of Tinemaha Reservoir Area

Two major pre-Cenozoic deformational events are recorded in this area. The first resulted in formation of the Strange Hill thrust and the Mule Spring syncline, which involve rocks as young as the Pennsylvanian–Early Permian Keeler Canyon Formation. These structures are overlapped by the Lower and Middle(?) Triassic Union Wash Formation. During the second episode the Union Wash Formation was folded twice; one event produced northwest-trending folds that appear to trend slightly more northwestward than the older Mule Spring syncline, and the other resulted in northeast-trending folds. These two folding episodes produced many folds with subvertical plunges. The minimum age of these deformations cannot be determined from relationships exposed near Tinemaha Reservoir, but can be by relationships exposed elsewhere (see subsequent discussion).

PERMIAN AND TRIASSIC EVENTS IN NEARBY AREAS

The Tinemaha Reservoir area is critical for interpretation of the Permian and Triassic history of east-central California because (1) it is situated in a geographically significant position relative to both the main mass of the Inyo Mountains and the eastern Sierra Nevada, (2) it contains key elements of the stratigraphy of both regions, and (3) evidence for major deformational events, which can be correlated with similar events in both the Inyo Mountains and the Sierra Nevada, is present. Here we consider the sequence of Permian and Triassic events represented in the Saddlebag Lake and Mount Morrison pendants in the Sierra Nevada and in the southern Inyo Mountains; this description is then followed by our regional correlations.

Saddlebag Lake Pendant

The geology of this pendant has been worked out by Schweickert and Lahren (1987, 1993), who assigned the sedimentary sequence overlying highly deformed lower Paleozoic rocks to the Permian Diablo and Lower Triassic Candelaria Formations. They also identified two major faults, the Golconda and Lundy Canyon thrusts. The Golconda thrust was active during or after deposition of the Candelaria Formation, which includes strata as young as late Early Triassic in west-central Nevada (Speed, 1984), and is cut by the Lundy Canyon thrust, which also cuts volcanic rocks dated at 222 ± 4 Ma. The Lundy Canyon thrust in turn is cut by a pluton dated at 219 ± 2 Ma (Schweickert and Lahren (1987). This thrust, therefore, is early to middle Late Triassic in age, and the older Golconda thrust must be late Early to early Late Triassic in age.

Mount Morrison Pendant

The northeastern part of this pendant (Fig. 1) is characterized by thrust faults with large, north-northwest–striking footwall synclines that commonly plunge subvertically and open in opposite directions (Stevens and Greene, 2000). Russell and Nokleberg (1977) recognized three sets of northwest-trending folds. According to Russell and Nokleberg, the third set is only sporadically developed and is younger than any of the structures discussed herein. Therefore, it will not be discussed further.

Russell and Nokleberg's (1977) earliest fold set included the map-scale, north- to northwest-striking synclines, as well as small-scale folds having an average trend of N8°W. One of the associated thrust faults (Nevahbe thrust) involves rocks assigned to the Pennsylvanian to Early Permian Mount Baldwin Marble, establishing a maximum age for this deformational event called the Morrison orogeny by Stevens and Greene (2000).

Russell and Nokleberg's (1977) second northwest-trending fold set in the Mount Morrison pendant consists of folds with small amplitudes and an average trend of N23°W; Wise (1996) showed a N28°W trend for folds presumably belonging to this set (Fig. 7B). In addition to these fold sets, Stevens (1998) and Stevens and Greene (2000) postulated a northeast-trending fold set that resulted in formation of the steep plunges in the north- to northwest-trending, map-scale synclines. One of the few folds of this set that has been identified is a moderately large, northeast-trending anticline that crosses the northwest-trending Sevahah Cliff syncline (Stevens and Greene, 2000). A second very large syncline with a kink-fold geometry is inferred at and northwest of McGee Mountain (Fig. 1) to explain the existence of subvertical folds that face one another at opposite ends of the outcrop belt (Stevens and Greene, 2000).

The origin of these steeply plunging folds is enigmatic. Stevens (1998) and Stevens and Greene (2000) postulated that the northwest-trending folds were refolded by northeast-trending folds formed along a regional restraining bend in the dextral proto–Laurel-Convict fault and that later sinistral displacement along the Laurel-Convict fault (Greene et al., 1997) brought those rocks against others lacking northeast-trending folds. Regardless, all sets of structures discussed here are cut by the Laurel-Convict fault, which in turn is intruded by a Middle to Late Triassic (225 ± 16 Ma) dike (Greene et al., 1997). Thus, all of these structures evidently are Permian to Triassic in age.

Southern Inyo Mountains

A complex history of Permian to earliest Triassic contraction has been documented in the southern Inyo Mountains where stratigraphic and structural relationships provide evidence for Early Permian development of the Fishhook and Lee Flat thrusts (of Stevens and Stone, 1988). Work in progress has led us to modify our earlier regional interpretation of these structures as reported by Stevens et al. (1997); we (Stevens and Stone, 2000) now consider them to be the frontal part of the Last Chance thrust system, as first suggested by Snow (1992). A second major deformational event in the region was marked by development of the Inyo Crest thrust and Upland Valley footwall syncline of Swanson (1996), which we now interpret to extend at least 70 km from the southern Inyo Mountains into the Last Chance Range (Fig. 1). These structures cut across or involve the Last Chance thrust in the southern Inyo Mountains, Dry Mountain, and the Last Chance Range. The Upland Valley syncline involves Leonardian and possibly younger Permian rocks and is unconformably overlapped by the Lower and Middle(?) Triassic Union Wash Formation, relationships that demonstrate a middle Permian to earliest Triassic age of deformation. This tectonic episode was followed by a period of relative quiescence during which the Union Wash Formation was deposited.

REGIONAL CORRELATION OF PERMIAN AND TRIASSIC EVENTS

The structural and age relationships just discussed permit recognition of four major Permian and Triassic events prior to development of the right-lateral Tinemaha fault and intrusion of plutonic rocks (Fig. 8). These include Early Permian and middle Permian–earliest

<table>
<tr><th>Area / Age</th><th>Saddlebag Lake</th><th>Mount Morrison</th><th>Tinemaha Reservoir</th><th>Inyo Mountains</th></tr>
<tr><td rowspan="5">Middle to Late Triassic</td><td colspan="2">Plutonism (Late Triassic)</td><td rowspan="2">?</td><td rowspan="5">?</td></tr>
<tr><td rowspan="2">?</td><td>Sinistral movement on Laurel-Convict fault</td></tr>
<tr><td colspan="2">Dextral movement on Tinemaha fault?</td></tr>
<tr><td>Lundy Canyon thrust</td><td rowspan="2">NE & NW-trending folds; Dextral movement on proto-Laurel-Convict fault?</td><td rowspan="2">NE & NW-trending folds</td></tr>
<tr><td>Golconda thrust</td></tr>
<tr><td>Early and Middle(?) Triassic</td><td>Marine sedimentation (Candelaria Fm.)</td><td>?</td><td colspan="2">Marine sedimentation (Union Wash Fm.)</td></tr>
<tr><td>Middle Permian-earliest Triassic</td><td rowspan="2">?</td><td>N- to NW-trending folds & thrust faults</td><td>Mule Spring syncline, Strange Hill thrust</td><td>Upland Valley syncline, Inyo Crest thrust</td></tr>
<tr><td>Early Permian</td><td>?</td><td>?</td><td>Lee Flat, Fishhook, Last Chance thrusts</td></tr>
</table>

Figure 8. Correlation of major Permian and Triassic geologic events in east-central California.

Triassic contractional events separated from complex Middle and/or early Late Triassic contractional events by an Early to Middle(?) Triassic period of marine sedimentation. These four events occurred prior to plutonism and the development of the right-lateral Tinemaha fault.

Early Permian and Middle Permian–Earliest Triassic Deformations

Two deformational events of Early Permian and middle Permian–earliest Triassic age, resulting in development of the Last Chance and Inyo Crest thrusts, respectively, are clearly differentiated in the southern Inyo Mountains where they are dated by the ages of the deformed rocks and the overlapping sequences. The Strange Hill thrust and associated Mule Spring syncline in the Tinemaha Reservoir area were formed between Pennsylvanian and Early Triassic time and thus could correlate with either deformational event in the southern Inyo Mountains. The structural style, scale, and orientation of the Strange Hill thrust and Mule Spring syncline, however, are much more similar to those of the Inyo Crest thrust and Upland Valley syncline than to those of the Last Chance thrust and related structures. On this basis we consider these structures at Tinemaha Reservoir to correlate with the middle Permian–earliest Triassic event (the Inyo Crest thrust event).

The first-generation folds of Russell and Nokleberg (1977) in the Mount Morrison pendant, including the map-scale folds interpreted to be footwall synclines by Stevens and Greene (2000), are dated only as Permian or Triassic. However, they also are very similar in structural style, scale, and orientation to the Mule Spring syncline at Tinemaha Reservoir and the Upland Valley syncline in the southern Inyo Mountains. All of these synclines are associated with thrust faults of apparently similar character. Therefore, all these structures are considered to belong to the same middle Permian–earliest Triassic deformational event.

Early to Middle(?) Triassic Sedimentation

Contractional deformation during Permian to earliest Triassic time was followed by a period of rapid subsidence throughout the region. In the southern Inyo Mountains and Tinemaha Reservoir area, the primarily fine-grained Union Wash Formation was deposited. In the Saddlebag Lake pendant in the eastern Sierra Nevada (Schweickert and Lahren, 1987) and in western Nevada (Speed, 1977, 1984), the essentially coeval Candelaria Formation accumulated. These two Triassic formations represent deposition in marine environments but in significantly different tectonic settings on the subsiding continental margin.

Middle and/or Late Triassic Contraction

Two sets of folds are represented in the Lower and Middle(?) Triassic Union Wash Formation near Tinemaha Reservoir. The minimum age is uncertain, but can be inferred from relationships in the Mount Morrison pendant where two similar sets of folds also are present. The folds at Mount Morrison include the second generation of northwest-trending folds of Russell and Nokleberg (1977) and the northeast-trending set of Stevens and Greene (2000). We suggest that these folds in the two areas are correlative because of their substantial geometric similarities, especially in the fold hinge lines measured by us near Tinemaha Reservoir (Fig. 7A) and those measured by Wise (1996) in the northeastern part of the Mount Morrison pendant (Fig. 7B). Because none of the folds in the northeastern part of the Mount Morrison pendant discussed here is younger than the latest movement on the Middle to Late Triassic Laurel-Convict fault, these proposed correlations, if valid, also limit the age of the folds near Tinemaha Reservoir (Fig. 8).

In the Saddlebag Lake pendant, two faults, the Golconda and Lundy Canyon thrusts, developed during Middle to Late Triassic time. One or both of these thrusts may be coeval with development of the second-generation northwest-trending folds in the Tinemaha Reservoir area and the Mount Morrison pendant

Middle to Late Triassic contractional deformation correlative with that recognized near Tinemaha Reservoir and in the eastern Sierra Nevada has not been recognized with any certainty elsewhere in east-central California. Two sets of folds have been recognized in the central White Mountains, a northeast-trending set having formed prior to a northwest-trending set (Morgan and Law, 1998), but it is not known if or how these folds correlate with those near Tinemaha Reservoir and in the Mount Morrison pendant.

Tinemaha Fault (Middle or Early Late Triassic?)

The Tinemaha fault, inferred to underlie Owens Valley (Fig. 1), is a cryptic structure along which Stevens et al. (1997) proposed that the rocks of the Tinemaha Reservoir area are displaced ~65 km in a right-lateral sense from rocks in the northeastern part of the Mount Morrison pendant. The existence of this fault is based on the apparent offset of (1) a major Devonian submarine channel, (2) similar structural features (including the only known areas with vertically plunging folds), and (3) the initial $^{87}Sr/^{86}Sr = 0.706$ isopleth (Kistler, 1993). Because the Tinemaha fault apparently displaces folds that involve the Union Wash Formation in the Tinemaha Reservoir area, it can be no older than Early to Middle(?) Triassic. Its precise trace and upper age limit are less certain. The fault must lie east of the eastern Sierran pendants and probably east of rocks in small outcrops ~7.5 km southwest of Bishop and at Arcularius Ranch (Bp and AR, respectively, in Fig. 1), which are lithologically similar to rocks in the Bishop Creek pendant. The fault also probably lies east of the Poverty Hills because the Late Pennsylvanian rocks exposed there are very different from those of the same age in the Mount Morrison pendant, which would restore adjacent to the Poverty Hills if the fault lay west of those hills. This inferred trace of the Tinemaha fault north of Tinemaha Reservoir (Fig. 1) apparently is crossed by the latest Triassic (ca. 210 Ma) Wheeler Crest Granodiorite of Bateman (1992). On the basis of these relationships, we interpret the Tinemaha fault to be Middle or early Late Triassic in age, although we realize that it could be younger because we cannot conclusively demonstrate that it is intruded by the Wheeler Crest Granodiorite.

The Tinemaha fault is similar in concept to the late Mesozoic intrabatholithic break 3 (IBB3) of Kistler (1993), which was proposed to account for the dextral offset of the initial $^{87}Sr/^{86}Sr = 0.706$ isopleth in the eastern Sierra Nevada. IBB3, however, was interpreted to coincide with the Laurel-Convict fault now known to be Triassic in age. We suggest instead that the major displacement occurred on the Tinemaha fault east of the Mount Morrison pendant, a location that also accounts for the apparent offset between rocks of that pendant and those in the Tinemaha Reservoir area.

DISCUSSION AND SUMMARY

The complexly deformed sedimentary rocks in the Tinemaha Reservoir area, ranging from Late Cambrian to Early and Middle(?) Triassic in age, include local structures that have caused considerable confusion and structures of regional significance that provide a basis for comparison of tectonic events between the Inyo Mountains and the eastern Sierra Nevada.

A prominent low-angle fault exposed in the area (here called the Big Hill fault), previously interpreted as part of a large-displacement thrust fault of presumed Mesozoic age (Inyo thrust), is reinterpreted as a probable Cenozoic low-angle normal fault of only local importance. The Inyo thrust, as originally conceived, is no longer considered to exist, although at least one fault originally included in the Inyo thrust zone (here called the Strange Hill thrust) is indeed a thrust fault.

Correlation of Permian and Triassic structures between the Tinemaha Reservoir area, the main mass of the Inyo Mountains to the east and southeast, and the eastern Sierra Nevada to the west and northwest provides the basis for a regional chronology of tectonic events. The earliest of these events resulted in development of the Early Permian Last Chance thrust. This fault probably underlies all of the area considered here, but it and associated deformational features apparently are exposed only in the eastern part of the region.

Effects of a second deformation, the Morrison orogeny as defined by Stevens and Greene (2000) in the eastern Sierra Nevada, produced east-vergent thrust faults and large footwall synclines. This orogenic event, dated as middle Permian to earliest Triassic and recognized throughout the region, is approximately coeval with the Sonoma orogeny as originally defined by Silberling and Roberts (1962) in northwestern Nevada.

The Morrison orogeny was succeeded by a period of quiescence during which the Union Wash and Candelaria Formations accumulated. Later, prior to the end of the Triassic, the western part of the region was deformed by two episodes of folding and displacement on the Golconda and Lundy Canyon thrusts. This deformation was followed by dextral displacement on the cryptic Tinemaha fault.

We speculate that these intense and tectonically diverse Permian and pre–middle Late Triassic events were the result of changing stress regimes associated with changing plate interactions that culminated in establishment of an east-dipping subduction zone and an associated magmatic arc in the latter part of the Late Triassic. Because of the constraints placed on the timing of deformational events in the Tinemaha Reservoir area, several tectonic events previously recognized in only the Sierra Nevada or southern Inyo Mountains can now be related and viewed as geographically widespread and regionally significant.

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