Post–2.6 Ma tectonic and topographic evolution of the northeastern Sierra Nevada: The record in the Reno and Verdi basins

Patricia H. Cashman¹, James H. Trexler, Jr.¹, Michael C. Widmer², and S. June Queen³

¹Department of Geological Sciences and Engineering, University of Nevada, Reno, Nevada 89557, USA
²Washoe County Department of Water Resources, Reno, Nevada 89502, USA
³Department of Geology and Geological Engineering, University of Mississippi, Oxford, Mississippi 38677, USA

ABSTRACT

A coarse conglomerate, known as “the Gravel of Reno,” fills a deep channel incised into a 2.6 Ma sedimentary section a few km west of Reno, Nevada. The canyon and its conglomerate fill record an abrupt shift in both provenance and paleocurrent direction compared with the underlying lake-marginal Neogene strata. Notably, the intermediate volcanic provenance of the Neogene section is supplemented in the overlying conglomerate by large plutonic clasts derived from the Sierran batholith. The syntectonic Gravel of Reno signals the initiation of Pleistocene faulting along the eastern edge of the Sierra Nevada near latitude 40° N.

Structures within the Neogene and Quaternary rocks reveal the progressive deformation of the Sierra Nevada’s eastern margin. There is no discordance between the basal Gravel of Reno conglomerate and the underlying Neogene sedimentary section, and both are presently tilted 23° east. Therefore, significant tilting did not occur until after channel incision and deposition of the basal conglomerate. The dip within the Gravel of Reno decreases with stratigraphic height, documenting ongoing tilting during deposition. Several pervasive fault sets cut the Neogene rocks; one set of normal faults probably predates much of the tilting, but strike-slip faults appear to have been active synchronously with it. Fault sets include early west- and northwest-dipping normal faults, and two mutually cross-cutting sets of strike-slip faults: northwest-striking dextral faults and northeast-striking sinistral faults. The most continuous mappable fault surfaces, with probably much of the most recent movement, are north-striking faults with normal or oblique-slip motion. Overall, these faults accommodate east-west extension. In summary, the structural style at the northern termination of the Carson Range is characterized by distributed slip along many minor faults, and faulting was synchronous with tilting of the sedimentary section.

Gravity studies constrain the location and geometry of the main structures as they project eastward under the Reno basin. A negative anomaly extends eastward from the east-trending Gravel of Reno. This gravity low (and the Gravel of Reno it represents) terminates eastward against a steep, north-striking gravity gradient under central Reno; we interpret this to mark a west-dipping normal fault, the “Virginia Street fault,” which was active throughout deposition of the coarse clastic section. A more localized and pronounced gravity low in west Reno corresponds to the eastward projection of the east-dipping Neogene diatomite that is exposed at the ground surface. The abrupt termination of this negative gravity anomaly requires that the diatomite terminates eastward at depth, therefore documenting the eastern margin of the Neogene lacustrine environment. Other gravity anomalies document both the relief on the sub-Neogene unconformity and a complex pattern of faults that offset Neogene and younger rocks in the Reno basin, consistent with the multiple fault sets seen in outcrop west of Reno.

INTRODUCTION

A number of questions about the Pleistocene–Pliocene evolution of western North America hinge on the timing and relative significance of two events: the creation of a high ancestral Sierra Nevada mountain range (i.e., the topographic high that predated the modern Sierran frontal fault system), and the formation of structural relief along the eastern margin of that range (i.e., the formation of the modern Sierran frontal fault system). For example:

(1) Was the west slope of the Sierra high in Paleogene time (e.g., House et al., 1998; Mulch et al., 2006; Cassel et al., 2009), or was a pulse of late Neogene uplift responsible for much of the modern elevation of the range (e.g., Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001; Stock et al., 2004)?

(2) Were there four Neogene faulting events in the northern Sierra Nevada (Busby and Putirka, 2009), two Neogene faulting events, one between 13 and 8 Ma and the other around 3 Ma (Henry and Perkins, 2001), or something else?

Other questions involve the timing and relative importance of NW-striking dextral slip and E-W extension along the boundary between the Basin and Range and the Sierra Nevada.

(1) Has Basin and Range normal faulting propagated westward into the Sierra Nevada with time (e.g., Dilles and Gans, 1995; Surpless et al., 2002), and did this faulting start more recently in the northern Sierra than in the central Sierra (e.g., Colgan and Dumitru, 2003; Lerch et al., 2004)?

(2) Motion of the Sierra Nevada microplate relative to stable North America, particularly the dextral component of motion, has been proposed to explain the strain recorded by earthquakes (e.g., Unruh et al., 2003) and the global positioning system (GPS) velocities (e.g., Hammond et al., 2011) along the Sierran frontal fault system. Does the Sierra Nevada–Basin and Range transition zone record dextral slip, uniform transtension, east-west extension, or some systematic combination of these, e.g., strain partitioning (Surpless, 2008)?

Yet other questions pertain to the tectonic driving forces behind the formation of the modern Sierra Nevada:

(1) Was either uplift or formation of the modern frontal fault system synchronous along the length of the range, or did faulting propagate north in parallel with migration of the triple junction along the plate boundary?
Is the timing of Neogene faulting consistent with the opening of the Gulf of California ~6 Ma (Oskin and Stock, 2003) or with crustal delamination of the Sierran root (e.g., Ducea and Saleeby, 1998; Feldstein and Lange, 1999; Manley et al., 2000; Farmer et al., 2002)?

Good sedimentologic, stratigraphic, and structural data from Pliocene–Pleistocene rocks are needed to address these problems but can be hard to find because rocks of this age are generally not exposed. Geodesy and seismicity studies establish the modern deformation, neotectonic studies document the recent faulting history, and stratigraphic and structural studies clarify conditions at specific times in the geologic past. However, it is often difficult to bridge the gap between contemporary tectonics and the older geologic record. The Neogene sedimentary rocks that record this time period are commonly still in depositional basins, buried by younger sediments.

The Reno-Verdi area is a good place to determine the age and evolution of the Sierran frontal fault system in northwestern Nevada, because of its structural setting, and because it preserves an unusually accessible and detailed record of the late Pliocene–Pleistocene geologic history along the Sierran margin. The Neogene Verdi basin lies at the north end of the Carson Range west of Reno, Nevada (Figs. 1–3). Both the Sierran frontal fault system and the Walker Lane step west into the Sierra Nevada in this general area; the record in the sedimentary section constrains the location, structural style, and timing of both. Strata of the Neogene Verdi basin (~11 Ma–2.6 Ma) are tilted and exposed (Trexler et al., 2012, and references cited therein). Subsequent deposits, the Gravel of Reno and younger glacial-outwash terraces, are also exposed in the Truckee River corridor. These rocks crop out at the surface west of Reno, and dip east; they can be traced eastward into the Reno basin in the subsurface, based on both drill-hole and geophysical data. Together, these two sedimentary units record deformation history for the past 11 Ma. The Verdi basin and Gravel of Reno sedimentary rocks temporally overlap formation of the Sierran frontal fault system, as well as a possible shift in style from mid-Tertiary east-west extension to subsequent transtension, as proposed by Faulds et al. (2005a, 2005b).

In this paper, we describe stratigraphic and structural features that document the formation of the eastern margin of the Sierra Nevada near Reno, Nevada, during Pleistocene time. After a review of previous work and its tectonic significance, we describe a remarkable syntectonic conglomerate, the Gravel of Reno. We show the evidence for base-level drop of >100 m and channel incision prior to deposition of the Gravel of Reno, and for progressive syndepositional tilting of as much as 23° that postdates the channel incision. We describe the pervasive fault sets in Neogene rocks and the internal deformation they record. We then present our gravity data, which allow us to project the major geologic features eastward under the Quaternary cover in the Truckee Meadows (i.e., the modern topographic basin occupied by the city of Reno, Nevada). We conclude with a summary of the evolution of the Sierran margin near Reno in the past 2.6 Ma and some implications of this study.
Localities mentioned in the text:
A. University of California plant locality #102 (Axelrod, 1958) "Verdi flora"
B. Chalk Bluffs diatomite, 4th Street
C. Mayberry Park
D. Stoker Ave
E. Mt. Rose piedmont

Figure 2. Simplified Reno-Verdi basin geologic map, modified from Trexler et al. (2000). Letters identify localities mentioned in the text. Labeled highways (80, 395, and McCarran Blvd.) are also shown on Figures 3 and 11, to aid comparison between figures.
Figure 3. Geologic map of the Truckee River corridor, showing the Quaternary outwash terraces and the Gravel of Reno; mapping is from Bell and Garside (1987), Bonham and Bingler (1973), and Bonham and Rogers (1983). Numbers identify localities mentioned in the text. Interstate 80 is shown for location purposes; it is also shown on Figures 2 and 11.
BACKGROUND

As reviewed in Trexler et al. (2012), the present consensus is that the ancestral Sierra Nevada was high by Eocene time, and sloped downward from the San Joaquin seaway to the west (e.g., Cecil et al., 2004, 2006, 2010; Mulch et al., 2006). An emerging consensus is that interior Nevada, to the east, was a high plateau, the “Nevadaplano” of Decelles (2004) (e.g., Ernst, 2009, and references therein), and that Oligocene tuffs with sources in central Nevada flowed west beyond the present Sierran divide through paleovalleys (e.g., Faulds et al., 2005b; Garside et al., 2005; Busby et al., 2008; Colgan and Henry, 2009; Hinz et al., 2009). The subsequent creation of local relief on the east side of the Sierran produced a topographic divide between the Great Basin and the west slope of the Sierra. The nature and timing of this event should be evident from the provenance and paleogeographic information preserved in the coeval sedimentary rocks.

Several other lines of evidence point to young (Pliocene–Pleistocene) Sierran uplift. Landscape analysis of the modern Feather River drainage and the position of young and high volcanic rocks in California, northwest of our study area, suggest rapid uplift since 2.8 Ma (e.g., Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001; Kemp and Wakabayashi, 2010a, 2010b). These authors propose that the uplift was accommodated by the Sierra Nevada frontal fault system (Fig. 1), and propagated north. Similarly, geomorphic analysis of west-flowing drainages in the northern Sierra and Lake Tahoe regions has been interpreted to indicate uplift and westward tilting 4–5 Ma, and initiation of normal faulting in the Lake Tahoe basin “later than about 3 Ma” (Schweickert, 2009). Neogene sedimentary rocks at Boca reservoir and the Verdi-Mogul area west of Reno (Fig. 1) record lacustrine conditions as recently as 3 Ma, and have subsequently been tilted and faulted (Trexler et al., 2000; Henry and Perkins, 2001; Mass, 2005; Mass et al., 2009; Trexler et al., 2012). Rapid rates of modern uplift are also indicated by geodetic data. Global positioning system and interferometric synthetic aperture radar (InSAR) data document contemporary vertical motion of 1–2 mm/yr for the length of the Sierra Nevada from 35° to 40°N, which could have generated the entire modern range in 3000 m.y. (Hammond et al., 2012). However, this uplift rate for the Sierra Nevada as a whole does not apply directly to the Carson Range, which is detached from the main body of the Sierra Nevada–Great Valley microplate. Active west-side-up motion is accommodated in part along faults in the Tahoe basin (e.g., Kent et al., 2005; Kent, 2010; Hunter et al., 2011) as well as along the Genoa fault on the east side of the Carson Range (e.g., Ramelli et al., 1999; Surpless, 2008; Cashman et al., 2009) (Fig. 1). The kinematics of Carson Range uplift change along the length of the range—displacement on the Genoa fault decreases northward to where the east flank of the Carson Range near Reno is an east-dipping homocline—but the details of geometry and timing of the deformation are poorly understood.

The partially exhumed Miocene–Pliocene rocks of the Reno-Verdi basin (“Sandstone of Hunter Creek” of Bingler, 1965) record the paleogeography—and local tectonic quiescence—of the area between ~11 and 2.6 Ma. First described as part of the Truckee Formation by the 40th Parallel Survey (King, 1878), these rocks were subsequently studied in more detail (Campbell, 1908; Bingler, 1965; Trexler et al., 2000), culminating in a detailed internal stratigraphy and paleogeographic interpretation, paraphrased below, by Trexler et al. (2012). There is no evidence of a major topographic barrier to the west when these rocks were deposited, although the modern Sierran Nevada forms a topographic barrier there today. There was no orographic rain shadow. Coarse, monolithologic boulder conglomerate is exposed at the base of the Verdi basin section in one locality, and suggests that there was an episode of faulting approximately synchronous with basin formation ~11–10 Ma. The deep weathering profile in the underlying bedrock suggests tectonic quiescence prior to that time. Notably, there are no monolithologic boulder conglomerates elsewhere in the Sandstone of Hunter Creek, and there are no internal unconformities, fault-related sedimentary deposits, fanning of dips, or other indications of active structural deformation during the time interval recorded by the Sandstone of Hunter Creek (i.e., after basin formation). Volcanic edifices similar to the Cascade Mountains of today dominated the topography, and river and lake sediments accumulated in small, inter-volcanic basins. The sedimentary rocks were volcanioclastic strata; kilometer-scale lakes accumulated diatomite and occasional air-fall tuff. Rivers were small and carried mostly silt, sand, and pebble gravel. Crystalline basement was not locally exposed during most of this time, so contributed little sedimentary debris. Similarly, the Neogene sedimentary strata were not exhumed and exposed to erosion anywhere in the area.

The Gravel of Reno, a pebble-cobble fluvial gravel informally named by Birkeland (1968), postdates the Sandstone of Hunter Creek and is exposed along 4th Street west of Reno (Fig. 3). It is mapped in a <2 km strip on the Reno geologic folio map (Bonham and Bingler, 1973), and we have identified another exposure nearby to the west. Birkeland (1968) noted the presence of granitic clast types and the evidence for post-depositional tilting of as much as 9°. He suggested that the aggradation might be related to “tectonic movements in the Truckee Meadows area” (p. 484). No datable material has been found in the Gravel of Reno, due to the difficulty of dating coarse, oxidized fluvial sediments and to the limited exposure of the unit. New ages of 2.61 Ma within the upper Sandstone of Hunter Creek (Trexler et al., 2012) provide the best age constraint. They are consistent with the previous estimates, and confirm that the Gravel of Reno is <2.61 Ma and is therefore Quaternary (Pleistocene) in age.

Most of the Quaternary sedimentary strata in the Reno-Verdi basin are related to glacial outwash. Preserved glacial deposits are correlated with four major periods of glaciation recognized in studies around Truckee, California (Birkeland, 1964). From oldest to youngest, the glacial advances are named the Hobart, Donner Lake, Tahoe, and Tioga (see Fig. 4 and references in the caption). Sediments related to these glacial events in the west Reno basin form pediments, and mainstream cut, strath, and fill terraces, deposited by the modern Truckee River system established in the Pleistocene. Eight terrace surfaces are recognized and mapped in the modern Truckee River corridor between Verdi and Reno (Bell and Garside, 1987) (Fig. 3). Birkeland (1964) related terraces Q1 through Q5 to Hobart and Donner Lake glacial advances, Q4 to Tahoe I glaciation, and Q3 and 2 to Tahoe II glaciation. However, the youngest (Tioga) periglacial deposits are not differentiated in the Verdi-Reno area and are mapped as part of the modern fluvial floodplain (Mock, 1972; Trexler and Cashman, 2007). Pleistocene outwash deposits have been recognized as far to the east as Mustang, Nevada, in the lower Truckee River canyon east of Reno (Birkeland, 1968).

The Neogene Verdi basin rocks (“Sandstone of Hunter Creek”) are preserved in a broad east-plunging syncline roughly coincident with the Truckee River valley through Verdi and western Reno, Nevada (Figs. 1 and 2). This structural low forms a re-entrant in the eastern margin of the Sierra Nevada. The syncline appears to have formed passively, between the north-plunging Carson Range uplift to the south and the Peavine Mountain uplift to the north, rather than as a buckle fold recording north-south shortening. The structure plunges east, particularly at its eastern end, reflecting the uplift of the Sierra relative to the Truckee Meadows since 2.61 Ma. The syncline along the Truckee River corridor is cut by several faults with offsets of tens or hundreds of meters, and by numerous mesoscopic
Figure 4. Time correlation chart for late Tertiary and Quaternary geologic units and events. The Cenozoic scale is from the GSA 1999 geologic time scale (Palmer and Geissman, 1999). Events and climatic conditions shown on Figure 4 were compiled from Jansen et al. (1986), Phillips et al. (1990), Clark and Gillespie (1997), Adams and Wesnousky (1999), Zachos et al. (2001), Szeicz and MacDonald (2001), James et al. (2002), Gillespie et al. (2004), and Solomina et al. (2007).
faults (e.g., Thompson and White, 1964; Bell and Garside, 1987; Trexler et al., 2000; Cashman et al., 2002; Cashman and Trexler, 2004).

The structure of the Truckee Meadows is incompletely understood. The Carson Valley, 40 km south of Reno, is a west-tilted half-graben bounded by the east-dipping Genoa fault (part of the Sierran frontal fault system) along the edge of the Carson Range (e.g., Cashman et al., 2009, and references therein) (Fig. 1). Quaternary fault scars of the Mount Rose fault system, offsetting the pediment at the southwest edge of the Truckee Meadows, have been interpreted as the northward continuation of the Genoa fault system (e.g., dePolo et al., 1996; Ramelli et al., 1999). This implies that the major basin-bounding fault system in the Truckee Meadows is east dipping, and is along the west side of the basin. However, a conformable section of east-dipping Miocene volcanic rocks and Neogene sedimentary rocks forms a homoclinal dip slope on the east flank of the Carson Range (e.g., Thompson and White, 1964; Bonham and Rogers, 1983; Trexler et al., 2012). No significant east-dipping fault has been identified in this area. This east-dipping section on the west flank of the modern basin indicates that the Truckee Meadows has the opposite asymmetry of the Carson Valley, and the basin-bounding fault is instead a west-dipping normal fault somewhere to the east of the Carson range front.

Geophysical and drill-hole data provide additional controls on the subsurface structure in the Truckee Meadows–Reno area. Gravity data show basin depths (encompassing both Neogene and Quaternary basin fill) of less than 0.5 km throughout most of the Truckee Meadows (Abbott and Louie, 2000). Their depth-to-bedrock map shows the maximum basin depth to be along the Truckee River corridor in the northwestern part of the basin; a bedrock ridge separates this from a second, less significant, sub-basin in the northeastern Truckee Meadows (Fig. 7 in Abbott and Louie, 2000). Notably, no linear bedrock trough exists along the edge of either the Carson Range (to the west) or Virginia Range (to the east), as would be expected for a simple subsurface west-dipping or east-dipping half-graben, respectively. Drill-hole data from a few deep geothermal wells and one wildcat oil well are consistent with basin depth estimates based on gravity (see Abbott and Louie, 2000, and references therein).

**PLEISTOCENE STRATIGRAPHY**

The Gravel of Reno and younger glacial outwash deposits document the changes in the local paleogeography during Pleistocene time. Changes in clast size, clast composition, paleo-current direction, or depositional environment may record changes in climate and/or tectonic setting.

The “Gravel of Reno”

The Gravel of Reno is a Pleistocene unit, deposited unconformably on the Sandstone of Hunter Creek. Strata near the top of the Sandstone of Hunter Creek have been dated at 2.61 Ma (Trexler et al., 2012). Conglomerates in the Gravel of Reno contain glacially polished and striated clasts as well as granite from Sierran sources. These clasts are the first evidence in the section of a glacial source for the sediment. Although the conglomeratic nature of the Gravel of Reno could be attributed to the change to glacial conditions in the Sierra Nevada, field relationships (see below) require an associated tectonic event.

The base of the Gravel of Reno is a deeply incised erosional unconformity cut into the Neogene Sandstone of Hunter Creek. A railroad cut beneath West McCarran Boulevard’s Truckee River overpass reveals a paleocanyon a minimum of 100 m deep carved into the Tertiary deposits (Fig. 5). The basal fill of the paleocanyon comprises very coarse conglomerate, including large rounded granite clasts and 2 m wide blocks of sandstone from the subjacent Neogene strata. The latter show evidence of being poorly consolidated, and are interpreted as canyon-wall blocks that fell into the canyon as it was being cut and subsequently filled. The fact that these blocks do not appear to have been completely lithified at the time the canyon was filled suggests that the Gravel of Reno is not much younger than the <2.61 Ma rocks on which it is deposited. Paleocurrent indicators, mainly cobble imbrication and tabular cross-bedding, indicate an abrupt shift in flow direction from east in the underlying sandstone to southeast and south in the Gravel of Reno. Notably, the inclination of bedding (i.e., paleohorizontal) above and below the unconformity is the same, ~23° east. Therefore, all of the present dip is due to postdepositional (tectonic) tilting, and there was no primary dip at the base of the Gravel of Reno.

A stratigraphically higher part of the Gravel of Reno is well exposed in one south-facing exposure along west 4th Street (old U.S. 40), where the sediment was apparently quarried for construction material (Figs. 3 and 6). This is the exposure mapped and described by Birkeland (1968); the dip here is less steep than it is at the base of the section. Bedding consists of thick, stratified conglomerate units that are interpreted as fluvial channel and bar features, including large (1–2 m thick) bar foresets, imbrication, and overbank sand bodies. Maximum clast size increases upward. Glacially polished and striated clasts occur in this part of the section. The top of the unit is not exposed, and its contact relationships with overlying strata are unknown.

**Terraces and Pediments**

The dominant geomorphic feature of the west Reno and Verdi valleys is a series of terraces and pediments that mantle the tilted Tertiary sedimentary rocks (Fig. 7). Bell and Garside (1987) mapped a series of eight terraces and related pediments on both sides of the river from Reno upstream past Verdi (Fig. 3). These terrace deposits are cut, stratified, and fill, comprising very coarse conglomerate with a variety of clasts, including intermediate and mafic volcanic rocks and commonly granite. As discussed later in this paper, Birkeland (1968) measured a gentle east tilt near the westernmost exposures of these terraces; farther to the east, they are buried beneath the Quaternary alluvium. The oldest terraces are the most steeply tilted (Fig. 4 in Birkeland, 1968).

**Sediment Composition and Provenance**

The dramatic shift in grain size and paleo-current direction across the basin unconformity of the Gravel of Reno is accompanied by a change in composition (Fig. 8). Whereas sand composition in the Sandstone of Hunter Creek is dominantly litharenite, the sand in the overlying Gravel of Reno is quartz-litharenite (Fig. 8A). In addition to the significantly higher percentage of quartz in the Gravel of Reno, in most cases it also contains more feldspar than the Sandstone of Hunter Creek. Conglomerate clasts in the Sandstone of Hunter Creek are a wide variety of volcanic compositions, and do not include granite except very locally at the basal contact. In contrast, the Gravel of Reno includes abundant granite in addition to a variety of volcanic rocks (Fig. 8B). Soft blocks and deformed slabs of light-colored, fine-grained sedimentary rock also occur as clasts in the Gravel of Reno. These are interpreted as eroded blocks of subjacent Sandstone of Hunter Creek.

In the Quaternary outwash terrace deposits, composition of sand-size material is dominantly volcanic lithic grains, with >10% feldspar and 10%–40% quartz (Fig. 8A). Gravel clast counts identified by terrace number (Fig. 8B) show a range of clast types. Notably, granite and monzonite are common, and sometimes dominant, throughout the terrace series. All of the clast sources can be identified in the modern Truckee River watershed.

Distinctive granitic boulders containing black tourmaline sprays and prominent pink potassic
feldspar (shown as “monzonite” in Fig. 8B) are found in many of the outwash deposits and in the Gravel of Reno, but not in the Sandstone of Hunter Creek. Rocks of this type are limited to the area between Donner Pass and Floriston, California (Hudson, 1951; L. Garside, 2006, personal commun. to J. Queen).

In summary, the composition of the Gravel of Reno resembles that of the Quaternary outwash deposits and differs from that of the Sandstone of Hunter Creek (Fig. 8A). The Sandstone of Hunter Creek is primarily litharenite with volcanic clasts, and was derived from volcanic source rocks. The overlying Gravel of Reno and Quaternary outwash deposits are primarily quartz-litharenite and contain granite and monzonite clasts. They record the presence of granitic as well as volcanic rocks in the source area; the tourmaline-bearing monzonite clasts document a source within the Sierra Nevada for both the Gravel of Reno and the Quaternary outwash deposits.

**Age Control**

Age estimates for the Gravel of Reno are only slightly better constrained now than those reported by Birkeland (1968) (Fig. 4). New isotopic ages from the Sandstone of Hunter Creek (the upper part of the underlying Neogene sedimentary section) provide an older age bracket of 2.61 Ma (Trexler et al., 2012). The observation that the underlying rocks were not lithified when they were eroded and incorporated as clasts into the Gravel of Reno suggests that deposition started not long after 2.6 Ma. Birkeland (1968) describes relationships showing that the Gravel of Reno is older than any of the outwash deposits exposed west of Reno.

Quaternary deposits in the Reno and Verdi basins comprise a sequence ranging in age from no older than ~2.5 Ma to less than 10 ka. The oldest mapped terraces may be ~1 Ma based on correlation with glacial deposits in the Truckee–Martis Valley area to the west (Birkeland, 1964) and on field relations with the McClellan Peak.
basalt to the east (Birkeland, 1968) (Fig. 3). Birkeland (1968) observed that Donner Lake outwash rests on McClellan Peak Olivine Basalt near Mustang, east of Reno. Although the flow is undated at Mustang, a recent ⁴⁰Ar/³⁹Ar date for the McClellan Peak basalt in the Chalk Hills, closer to its source, is 1.44 ± 0.01 Ma (Schwartz and Faulds, 2001). Terrace correlation west of Reno is based on mapping and correlation by Birkeland (1964, 1968) and Bell and Garside (1987): the oldest and highest terraces (Qt8 through Qt5) are thought to be between 1 Ma and 700 ky and may correlate with the Sherwin, Donner Lake, and/or Hobart glaciation. Middle-level terraces (Qt4) probably correlate to Tahoe I glaciation, ~140 ky. The youngest terraces (Qt3 and Qt2) are correlated with Tahoe II and Tioga glaciation and range in age from 34 ky to 11 ky.

STRUCTURE

Structures in the Neogene rocks record the structural style along this margin of the northern Sierra Nevada, and the cumulative deformation since 2.6 Ma. Structures in younger rocks may show progressive deformation during the Pleistocene.

The Pliocene–Pleistocene rocks of the Verdi-Reno area are cut by several fault sets and are tilted; all of these structures have formed in the past 2.6 Ma. Notably, the youngest part of the Neogene Sandstone of Hunter Creek section (including the horizon containing the 2.61 Ma grains) is primarily lacustrine and had a negligible primary dip, so all of the present dip is structural in origin. Most of the structures are best developed and preserved in the exhumed Neogene rocks exposed along the Truckee River corridor between Verdi and west Reno (Fig. 2), although even in these rocks, kinematic indicators are uncommon. The overlying Gravel of Reno and younger rocks are relatively poorly consolidated, so fault surfaces are generally not preserved in outcrop. However, tilted bedding with fanning dips records progressive deformation of these rocks during deposition. The geometric distribution of rocks and structures—Neogene rocks within the Sierra in a structural low, but younger rocks primarily in the Truckee Meadows basin to the east—is not as problematic as it first appears for distinguishing structures of different ages or locations. Quaternary terraces along the Truckee River corridor are developed on the Neogene rocks, permitting some comparison between rocks of different ages in the same location, and geophysical methods identify major subsurface structures below Quaternary cover.

Faults

The Pleistocene breakup of the east Sierran margin recorded in the rocks of the Verdi-Reno area is complex, involving several fault sets and reactivation of some fault surfaces (Fig. 9). Although fault offsets of tens (up to hundreds) of meters are common, the faults are seldom mappable very far laterally; deformation was accommodated along many relatively minor faults rather than along a few throughgoing ones. Kinematic indicators are not well preserved in the study area, and for purposes of this study, were measured only in the Neogene section, not the underlying intermediate volcanic or plutonic rocks. A road cut along West 4th Street (old U.S. 40) west of Reno exposes a long section of northeast-dipping faulted diatomite from the upper part of the Sandstone of Hunter Creek and illustrates the structural style (Figs. 9A and 9D). Nearly continuous exposures along an irrigation ditch farther west provide results consistent with the 4th Street road cut, distributed over a considerably wider area. The major faults (i.e., those with meters or tens of meters of slip) most commonly have subhorizontal striations. Two strike-slip fault sets are mutually cross cutting and were active simultaneously. The sense of slip on these faults is shown by kinematic indicators on the fault surfaces and, in some cases, by reorientation (drag folding) of nearby bedding. Several characteristics of the faults are consistent with ongoing faulting synchronous with tilting of the sedimentary section.

The oldest faults in the 4th Street road cut, northwest- to west-dipping normal faults, dip moderately (Fig. 9A) and have rotated from an
originally steeper dip as the bedding tilted east (Fig. 10A). Striae are only rarely preserved on this fault set, but when present are down dip (Fig. 10B); apparent offset is normal. Wherever the moderately dipping normal faults are observed in a cross-cutting relationship, they are older than (i.e., they are cut by) the other, steeper, fault of the pair (Fig. 10C).

Northwest- to north-northwest–striking faults have steep dips, subhorizontal slip indicators, and dextral offset (Figs. 9B and 10D). The three best preserved, large-offset dextral faults encountered in this study are associated with zones of drag folding several meters thick; bedding strike approaches parallel to fault strike at the fault. In one of these examples, the exposure was continuous enough to document 12 m of stratigraphic offset, in spite of the fact that bedding now strikes parallel to the fault. This relationship requires tens, if not hundreds, of meters of fault slip. The dextral faults commonly dip steeply west, rather than being vertical. In cases where one dextral fault cuts another, the steeper fault is younger, and the older, moderately dipping fault dips west (Fig. 10E). Both of these observations are consistent with formation of dextral faults throughout the eastward tilting of the sedimentary section, and the progressive tilting of older faults. Note that although apparent offset (as shown by matching beds across faults) is often visible, it can be misleading. It is the opposite of the true sense in cases where the slip direction plunges more steeply than the intersection of bedding with the fault surface. This is most apt to be the case for the dextral faults in the 4th Street road cut, because fault and bedding strikes are subparallel.

North-northeast– to east-northeast–striking faults have steep dips, subhorizontal slip indicators, and sinistral offset (Figs. 9C and 10F). Drag folds have also been observed adjacent to these faults. Many subparallel faults cut the 4th Street road cut, including ten or twelve sinistral faults with a stratigraphic separation of 1 m or more. The largest fault has a stratigraphic separation of more than 4 m (Fig. 9C). Like the dextral faults, sinistral faults that cut older sinistral faults usually have steeper dips than the faults they cut (Fig. 10G); this is consistent with rotation of older faults as the sedimentary section is tilted, accompanied by the formation of new subvertical faults. In addition, mutually cross-cutting relationships between the sinistral and dextral faults document that these two fault sets were active simultaneously, at least in part (Figs. 9D, 10B, 10E, 10G).

A few faults strike slightly east or west of due north and have oblique slip indicators (shown in yellow-green on Fig. 10B). These have dextral-normal oblique offset, and are often the youngest of cross-cutting fault surfaces. Map-scale faults show many of the same relationships as the small faults in the 4th Street road cut. Even faults that significantly offset lithologic units are often not mappable far laterally. For example, a northwest-striking fault east of Verdi (immediately east of locality A on Fig. 2) juxtaposes 10 Ma basalt and coarse conglomerate from the base of the Miocene section, on the east, against the fluvial deposits (obscured by Quaternary cover) that contain the early Pliocene “Verdi flora” (Axelrod, 1958) on the west.
Figure 9. (A) Northwest-dipping normal fault, photographed looking north. Although the fault dip on this road cut is atypically gentle because it is an apparent dip, faults in this set have moderate dips and are interpreted to have rotated from an originally steeper orientation as the bedding tilted eastward. The rock in this outcrop is lacustrine diatomite; marker horizons are air-fall tephra; bedding dips east. (B) Northwest-striking dextral fault exposed in a construction site when the excavation wall failed along the fault surface, photographed looking southeast. Steps in the fault surface document subhorizontal dextral slip. The rock in this outcrop is fine-grained fluvial and deltaic sandstone; bedding dips east. (C) Northeast-striking sinistral fault, photographed looking north. Marker horizons can be matched across the fault surface, recording ~4 m of stratigraphic separation. Grooves on the fault surface indicate subhorizontal slip. The rock in this outcrop is lacustrine diatomite; marker horizons are air-fall tephra; bedding dips east. (D) Mutually cross-cutting relationships between northwest-striking dextral faults and northeast-striking sinistral faults, photographed looking north. In this example, the oldest and youngest faults are sinistral. The rock in this outcrop is lacustrine diatomite; marker horizons are air-fall tephra; bedding dips east.
Figure 10. Stereograms of bedding and mesoscopic faults in Neogene diatomite in the Chalk Bluff road cut on 4th Street. See Figures 2 and 3 for the location of Chalk Bluff. (A) Poles to bedding in diatomite; N = 35. (B) Compilation of all measured faults that have at least 1 m of stratigraphic offset. Since most fault exposures are in road cuts or the walls of irrigation ditches and have limited vertical extent, it is impossible in most places to match stratigraphic markers across these faults. Stratigraphic offset may therefore be significantly greater than 1 m. The faults include four sets, coded by color on the stereogram: red—sinistral; blue—normal; yellow-green—dextral-normal oblique; blue-green—dextral. Striae, where present, are shown as open circles. (C) Crosscutting relationships consistently show the moderately west-to northwest-dipping normal faults to be the oldest. Older faults—blue line with dash-dot pattern. Younger faults—solid red line. The older faults dip moderately, and the younger faults dip steeply west, consistent with progressive rotation of faults as the bedding tilted toward the east. Three fault pairs. (D) Contoured poles to dextral faults; N = 24, contour interval = 4% per 1% area. (E) Crosscutting relationships where the younger fault in the pair is dextral. Older faults—blue line with dash-dot pattern. Younger faults—solid red line. Five fault pairs. (F) Contoured poles to sinistral faults; N = 68, contour interval = 2% per 1% area. (G) Crosscutting relationships where the younger fault in the pair is sinistral. Both northeast-striking (sinistral) faults and northwest-striking (dextral) faults are cut by younger sinistral faults. Older faults—blue line with dash-dot pattern. Younger faults—solid red line. Four fault pairs. Note that the relative age relationship shown here is the opposite of the relative age relationship shown in Figure 10E, above; together these demonstrate that these two fault sets were synchronous, and support the interpretation that the sinistral and dextral strike-slip faults are a conjugate pair.
The stratigraphic offset is at least 500 m. However, along strike to the northwest, this fault does not offset the basal Neogene contact. Instead, it terminates against lacustrine rocks low in the Neogene section, cut off by a poorly exposed northeast-striking fault. Similarly, several northeast-striking faults that offset the basement (KJ)-Tertiary contact northwest of Mogul (simplified on Fig. 2 to one fault north of the “Mogul” label) terminate against a north-striking fault. Although partly attributable to paleorelief on the sub-Neogene surface, poor preservation of weakly cemented rocks, or cover by vegetation or unconsolidated sediments, these discontinuous map relationships unequivocally document several fault sets, resulting in irregular blocks separated by short fault segments. In addition, the faults that offset the Tertiary section, and together, accommodate dextral-normal oblique-slip faults. These faults are the most continuous mappable faults, and they appear to be the youngest fault set.

In summary, the mesoscopic faults in the 4th Street road cut record: (1) early normal faults, subsequently rotated during tilting of the sedimentary section, (2) two sets of strike-slip faults that were active coeval with tilting of the sedimentary section, and (3) a few north-striking, dextral-normal oblique-slip faults. These faults repeat section, and together, accommodate roughly east-west extension. The faults in the 4th Street road cut appear to be representative of those in the study area along the Truckee River corridor, north of the Carson Range and south of Peavine Peak. The basal contact of the Neogene sedimentary rocks overlying Miocene andesite is offset by several faults, but lateral displacement along them is never more than 200–300 m (Fig. 2). Notably, the map relationships are inconsistent with significant dextral slip across this part of the Truckee River corridor, although dextral transtension characterizes the Walker Lane.

Postdepositional Tilt of Bedding

The broad, map-scale folds in the Neogene rocks in the Verdi-Reno area record cumulative post–2.6 Ma deformation, while tilt of the Gravel of Reno and younger sediments documents the incremental deformation. The Neogene section forms a broad, faulted syncline that appears to have formed passively between the north-plunging Carson Range to the south and the south-plunging Peavine Peak uplift to the north (Fig. 2). This syncline plunges east at its east end, recording uplift of the Sierran relatable to the Truckee Meadows. It is not possible to determine the structural relief represented by this structure quantitatively, because of lateral variations in distribution, thickness, and composition of the Neogene section (Trexler et al., 2012) and offset along subsequent faults.

Tilt of bedding in the Gravel of Reno is limited to fanning of dips due to syndepositional faulting. Bedding at the base of the Gravel of Reno section dips 23° east, parallel to bedding in the subjacent section (Fig. 4). At the 4th Street road cut 0.75 km to the east, it dips 11° at the lowest exposures and 7° at the highest ones. (Note: the 9° dip recorded in Birkeland [1968] was almost certainly measured in this road cut.) Raveled exposures on Stoker Avenue, 1.5 km still farther east, appear to dip more gently, but cannot be measured reliably.

Terrace Tilt History and Implications

The glacial outwash terraces along the Truckee River from Verdi to west Reno (Fig. 7) have also been interpreted to be progressively tilted eastward (Birkeland, 1968). Although Birkeland (1968) found the gradient of the glacial outwash terraces within the Sierra, near the town of Truckee, to be parallel to that of the modern Truckee River, he found that this was not the case for the easternmost exposures of what he believed to be correlative terraces immediately west of Reno. Deposits identified by Birkeland (1968) as “pre–Donner Lake” are tilted the most steeply, then Donner Lake outwash, then Tahoe outwash, documenting progressive eastward tilting during the past several hundred thousand to perhaps as much as one million years. An alternative explanation is that these outwash terraces preserve a shift from larger to smaller glaciations with time, and this is expressed as steeper depositional slopes on the older surfaces. However, these terraces near Reno are 80 km downstream from the glaciers, and it seems unlikely that deposits from smaller glaciations would be steeper at this distance. In either case, the change in dip in these outwash deposits is minor compared to the tectonic steepening recorded in the Gravel of Reno.

Most of the eastward fanning of bedding dips in the study area is recorded in the Gravel of Reno; the dip of even the oldest mapped terrace surfaces (Birkeland, 1968) is small by comparison. We interpret this to constraining most of the tectonic steepening of dip to between ~2.5 and ~1 Ma.

Kinematics—Summary

The structures in the Reno-Verdi area record both tilting and faulting during the post–2.6 Ma formation of the Sierran boundary. Dips in the Neogene section document uplift of the Carson Range and Peavine Mountain, and subsidence of the Truckee Meadows, relative to the present position of Neogene rocks in Verdi and Mogul, Nevada, and along the east flank of the Carson Range near Reno. Pervasive small faults in these rocks record east-west extension along conjugate strike-slip fault sets concurrent with the tilting. Eastward dips in the Gravel of Reno section (<2.6 Ma, >1.0 Ma) decrease upsection from 23° at the base to 7° in the youngest rocks preserved, proof of syndepositional slip along a bounding fault to the east of the modern range front. Smaller amounts of tilt noted by Birkeland (1968) in progressively younger outwash terraces (<1.0 Ma) suggest continued fault-controlled subsidence to the east during the most recent Pleistocene glaciations.

GRAVITY MODELING

Gravity modeling allows us to project the rocks and structures we describe eastward, under the Quaternary deposits of the Truckee Meadows. There is a strong density contrast between bedrock (here, Sierran plutonic or metamorphic rocks with the overlying intermediate volcanic rocks) and the poorly consolidated to unconsolidated Neogene and Pleistocene basin fill. The gravity anomalies reflect changes in rock density at depth and can be due to faults, paleotopography, and lateral facies or thickness changes. Basin depth can be inferred from the magnitude of the anomaly.

Methods

Gravity measurements for Figure 11 were compiled from several surveys (Abbott and Louie, 2000; Oppliger, 2002), but most of the data collection was contracted to Tom Carpenter, consulting geophysicist. Surveys were conducted from 2000 through 2005, during which over 200 gravity stations were measured within the hydrographic basin. Hundreds of additional regional gravity data points have been collected by Carpenter under other Washoe County contracts, and these data points have been singly processed for the compilation. The data were collected using a LaCoste and Romberg Model G-230 gravimeter with a precision of 0.01 mGal. Positions were located by rapid static GPS survey methods using a WILD GPS-System 300 manufactured by Leica. The elevation accuracy is believed to be better than ±20 cm. The 1971 International Gravity Reference Network base at the James G. Scrugham Engineering Mines Building at the University of Nevada, Reno, served as the local reference gravity value. The measured data were reduced
to complete Bouguer values using 2.50 g/cm³ as the Bouguer density.

Densities of the rock units were measured for use in the gravity modeling (169 measurements; see Table 1). Tertiary andesite (10 samples) and Mesozoic metavolcanic rocks (3 samples) have fairly consistent densities. Standard density values were used for the Mesozoic granodiorite. Tertiary and Quaternary sedimentary rocks are much more variable in grain size and density, and therefore make up the vast majority of the density measurements (Table 1). Densities of the sedimentary units were measured on both dry and water-saturated samples (Table 1).

Geologic cross sections used in the gravity modeling were drawn from the surface geology and supplemented where possible with borehole data (Fig. 12). The purpose of the modeling was to define distribution and thickness of Pliocene and Pleistocene sedimentary units for water resource purposes, so accurate depiction of the internal stratigraphy of these units was particularly important. Therefore, we used the established internal stratigraphy based on surface geology (Campbell, 1908; Bingler, 1965; Trexler et al., 2012) to subdivide the Sandstone of Hunter Creek into four model units: lower sandstone and conglomerate, mixed sandstone and diatomite, diatomite–silty diatomite, and upper sandstone, each with a separate density based on the density measurements (Table 2). Since our measurements show that the Gravel of Reno has a similar composition and density to the Quaternary outwash and fluvial deposits, all of these are included in the same model unit.

Modeling, using the GM-SYS software package, generated synthetic gravity profiles for the geologic cross sections (Fig. 12). These synthetic profiles were compared to the measured gravity on the same section line. The cross sections were then modified, within geologically reasonable constraints consistent with surface and borehole data, until the synthetic gravity profiles matched the measured gravity profiles as closely as possible (Fig. 12).

Results

Large positive anomalies in the east and northwest of Figure 11 reflect Mesozoic plutonic and metamorphic rocks at or near the ground surface. Scattered smaller positive anomalies are associated with exposures of Tertiary and Quaternary volcanic rocks. Negative anomalies show the locations where bedrock is deeper under the Truckee Meadows, and reveal structural complexity that is not apparent at the surface.

The deepest negative anomaly, centered on the intersection of the Truckee River and west McCarran Boulevard (near where section lines A and C cross on Fig. 11), is controlled by the low-density diatomite near the top of the Neogene section. This diatomite—and therefore the Pliocene paleolake—must terminate at the east edge of the negative anomaly; no other subsurface configuration consistent with the surface geology generates the observed gravity profile (Fig. 12, at approximately the 13,000 m mark on the horizontal scale on section A–A').

A steep gravity gradient under central Reno represents a north-striking, west-dipping normal fault bounding the east-dipping Gravel of Reno sedimentary wedge (Fig. 11). The steep gradient roughly coincides with Virginia Street through the center of Reno, so we refer to the inferred fault informally herein as the “Virginia Street fault” (shown as a white dashed line on Fig. 11). This fault formed <2.6 Ma ago, and was active during deposition of the Gravel of Reno and overlying glacial outwash deposits, as recorded in the progressive tilt of bedding in these units.

The fault-controlled gravity gradient dies out southward (Fig. 11), indicating that displacement along the Virginia Street normal fault decreases to the south and dies out against the dip slope on the east flank of the Carson Range. However, surface mapping, gravity studies, and seismic studies all document the presence of other faults farther south, where the Virginia Street fault dies out. A closed negative anomaly along the southern part of this fault (near where section line A–A’ crosses the Virginia Street fault on Fig. 11) requires a local diatomaceous section, probably initially ponded by the paleotopography. The negative anomaly was subsequently amplified by faulting (Fig. 12, at approximately the 17,000 m mark on the horizontal scale on section A–A').

Two additional sub-basins underlie the eastern half of the Truckee Meadows, but they are not as deep as the western sub-basin. There is no evidence for a prominent young fault like the “Virginia Street fault” along the east edge of the Truckee Meadows, but both paleotopography.
of the sub-Neogene surface and young volcanic rocks in the southeastern Truckee Meadows may obscure other gravity signals.

SUMMARY—GEOLOGIC HISTORY

The first evidence of a dramatic change in conditions is the incision of a deep paleochannel into the youngest lacustrine strata (<2.61 Ma) in the Sandstone of Hunter Creek. The lacustrine sediments were deposited at local base level. Canyon cutting documents a drop in base level to the east of at least 100 m. Our sedimentological and gravity evidence indicate that the lake was small, and not deep enough for lake desiccation to cause a base-level change of this magnitude. We attribute the base-level change to the end of the Carson Range south of Reno; instead, the eastern Sierra Nevada near Reno all formed at the highest place where it can be reliably measured. This eastward tilting continued throughout the Pleistocene, as recorded by progressively gentler eastward dips in the glacial outwash deposits (Birkeland, 1968). We believe that deposition of these outwash terrace gravels is a continuation of the Gravel of Reno history and is not a separate geologic event. In any case, these gravels represent a major Pleistocene reorganization of sediment source, watershed, depositional environment, and basin geography.

The dominant structural style in the Sandstone of Hunter Creek, at both macroscopic and mesoscopic scales, is distributed faulting along several sets of faults (Figs. 9 and 10). The distributed faulting was concurrent with eastward tilting. An early, west- to northwest-dipping normal fault set is only locally preserved. This normal fault set has been tilted with (and therefore, largely predates) the eastward tilt of the Sandstone of Hunter Creek sedimentary section. Subsequent faults accommodate dominantly east-west extension, primarily along a conjugate set of strike-slip faults. Notably, although the northwest-striking dextral fault set is subparallel to the Walker Lane and the transform plate boundary, displacement is not demonstrably greater on this than on the northeast-striking sinistral fault set.

DISCUSSION AND CONCLUSIONS

The Reno-Verdi study area straddles the eastern boundary of the Sierra Nevada, and occupies a structural low in a re-entrant along the range front. The Pliocene rocks preserved here record the paleogeography until ~2.6 Ma. The Pleistocene rocks were deposited during the breakup of the eastern Sierra margin, and thus they preserve a record of the timing and style of this event. The structural relief and elevation of the Carson Range die out northward; therefore, we can examine how deformation is accommodated along the trend of the range as well as across its branches.

New results from this study include:

1. The Pleistocene breakup of the eastern margin of the Sierra Nevada near Reno started less than 2.6 Ma and continues today. This is a younger and more precise date for this event than was previously known.

2. Rapid base-level drop and incision (Fig. 5) preceded eastward tilting in the Reno-Verdi area.

3. The east-tilted Neogene–Pleistocene section is bounded on the east by the Virginia Street fault (Figs. 11 and 12). The fault’s location, documented in this study by gravity modeling, was previously detected based on anomalous groundwater response to pumping tests near the fault trace (see discussion below).

4. Syndepositional slip along the Virginia Street fault produced cumulative dips of as much as 23° in the Gravel of Reno (<2.6) Ma, which is exposed west of Reno. Fanning of dips in this east-tilted half-graben is seen both in the surface exposures (Figs. 5 and 6) and in seismic reflection records to the east (Fraray et al., 2011).

5. Pervasive minor faulting in the Pliocene Sandstone of Hunter Creek (Fig. 9) was synchronous with tilting, as shown by progressive rotation of older faults and formation of new ones (Fig. 10).

6. The major structures along the eastern edge of the Sierra Nevada near Reno all formed <2.6 Ma. These include the north-plunging termination of the Carson Range, the south-plunging Peavine Mountain uplift, and the broad east-plunging syncline in the re-entrant between them, now occupied by the Truckee River valley (Figs. 1 and 2).

7. There is no major fault along the east slope of the Carson Range south of Reno; instead, the Neogene and Pleistocene sections form an east-dipping homocline offset by small normal faults, the “Mt. Rose fault system” (Fig. 2).

8. The Reno-Verdi study area does not record significant dextral motion in Pleistocene time, although it lies within the Basin and Range–Sierra Nevada transition zone. Like the Carson Valley to the south (Fig. 1) (e.g., Surpless, 2008; Cashman et al., 2009) but with the opposite polarity, the study area records primarily east-west extension.

9. The deposition of the Gravel of Reno is part of the glacial outwash history and not a separate geologic event, based on sand and conglomerate
Figure 12. Schematic geologic cross sections of the Verdi-Reno area based on surface geology and Bouguer gravity, constructed using the GM-SYS software package. We used the established internal stratigraphy of the Sandstone of Hunter Creek to divide it into four model units, each with a separate density (Table 2): lower sandstone and conglomerate, mixed sandstone and diatomite, diatomite–silty diatomite, and upper sandstone. Since the Gravel of Reno and the Q outwash deposits have similar compositions and densities, they are combined into one model unit, “Qal.” The locations of the section lines are shown on Figure 11. Abbreviations: l—lower; u—upper; V.E.—vertical exaggeration.
Reno can also be seen in the subsurface farther of dips at the ground surface in the Gravel of commun.). In an unrelated study, the fanning well (C. Benedict, WCDWR, 2006, personal tion. In contrast, more distant wells on the same Virginia Street fault exhibit little or no communica-

ing, the earthquake swarm is thought to have we have observed (e.g., Anderson et al., 2009).

The southwestern Truckee Meadows is an accommodation zone between a west-dipping fault system on the north and an east-dipping fault system on the south. Notably, there is not a strong, linear negative gravity anomaly along either edge of the Truckee Meadows, thus ruling out a simple half-graben structure like that of the Carson or Washoe valleys. The biggest single structure appears to be the Virginia Street fault, in the center of the valley. The Virginia Street fault terminates southward in an area of many other faults (Fig. 2) (Frary et al., 2009; Kell-Hills, 2010). The Genoa fault and a similar fault bounding Washoe Valley have the opposite polarity and terminate northward (Fig. 1). The area between them (e.g., the Mount Rose pied-

mont) is characterized by higher and irregular topography, with many small faults, horsts, and grabens. All these characteristics are consistent with an accommodation zone.

The east-dipping half-graben bounded by the Virginia Street fault, the accommodation zone in the southwestern Truckee Meadows, and the west-dipping half-graben bounded by the Genoa fault to the south are all consistent with approximately east-west extension across this part of the Sierra Nevada–Basin and Range transition zone. This extensional zone illustrates strain partitioning within the transtensional Walker Lane (e.g., Stewart, 1988; Cashman and Fontaine, 2000; Faulds et al., 2005a; Surpless, 2008, and many others) and is consistent with block models based on InSAR measurements and GPS velocities (e.g., Hammond et al., 2011, 2012).

The results presented here and in Trexler et al. (2012) corroborate two phases of Neogene deformation along the eastern edge of the modern Sierra Nevada as proposed by Henry and Perkins (2001), but with revised age control. The previous age constraints, from the Donner Pass–Boca reservoir area in the Sierra Nevada west of our study, were a 13 Ma–8 Ma bracket on the older faulting event and a <3.1 to >2.6 Ma bracket for the second (Henry and Perkins, 2001). A detailed study at Boca Reser-

voir restricted the age range for faulting, tilting, and breakup of the sedimentary system there to between ~2.75 and 2.61 Ma (Mass, 2005; Mass et al., 2009). Evidence from the Reno-Verdi area constrains an early faulting event (inferred from the presence of a monolithic boulder con-

glomerate at the base of the Neogene section) to ~11.5–10.5 Ma. The later tilting and faulting unequivocally started <2.61 Ma and continued well into the Pleistocene and probably to the present. The difference between these well-constrained age brackets for the Pleistocene event suggests that the faulting and tilting were short lived at Boca Reservoir and may then have stepped eastward to the Verdi-Reno area.

The Carson Range, and by inference, the northern Sierra Nevada, has moved up, and the Reno basin down, relative to the present position of the Pliocene–Pleistocene rocks exposed in the Reno-Verdi area. Lacustrine rocks in the upper part of the Sandstone of Hunter Creek were deposited as horizontal beds across the modern range front ~4.5–3 Ma. They now dip east along the east flank of the Carson Range, and form an east-plunging syncline in the re-

entrant north of the Carson Range. The dramatic unconformity cut into the Sandstone of Hunter Creek (Fig. 5) documents a drop in base level of at least 100 m, and the canyon-filling Gravel of Reno contains clasts derived from the interior of the Sierra to the west (Fig. 8). The conglomeratic rocks in the Gravel of Reno probably reflect higher discharge and sediment load due to glaciation in the Sierra Nevada, but they also record syndepositional eastward tilting and faulting along the Virginia Street fault to the east. This evidence for recent formation of the modern topography is consistent with long-

standing paleobotanical evidence that there was no Pliocene rain shadow (e.g., Axelrod, 1958), but provides tighter, and younger, age control. The modern uplift documented by GPS and InSAR data (e.g., Hammond et al., 2012) is most likely the continuation of this uplift event.

In conclusion, the record presented here from the Reno-Verdi area tightly constrains both the timing and the style of latest Pliocene–Pleisto-

cene faulting and tilting in one locality along the eastern margin of the Sierra Nevada. Combined with similar well-controlled data points elsewhere along the Sierran margin, this will help resolve questions about propagation or synchronicity of
fault initiation throughout the region. Ultimately, these questions address the tectonic controls on fault initiation throughout the region. Ultimately, these questions address the tectonic controls on fault initiation throughout the region.

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