Sedimentation, faulting, and erosion in the Carlin basin, northeastern Nevada, and implications for mineral exploration and ground water resources

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ABSTRACT

New mapping in the Carlin basin in northeastern Nevada near Carlin shows that the present sediment-filled topographic basin is a product of both Miocene sedimentation and faulting and Pliocene and younger erosion. Early south-directed alluvial-fan sedimentation began at or shortly before 15.2 Ma, depositing debris flows, conglomerates, and sand derived from the southern Tuscarora Mountains and Swales Mountain areas and finer-grained alluvial sediments from smaller streams sourced in the Adobe Range, northern Piñon Range, and Marys Mountain areas. These sediments interfingered with lacustrine sediments that were deposited in a shallow lake centered in the southern part of the basin. The lake extended beyond the southern ends of the modern Adobe Range and Marys Mountain, indicating low relief in those areas. Eruption of the 15.2 Ma Palisade Canyon rhyolite in the southwestern corner of the basin may have dammed through-going streams and caused the synchronous formation of the lake and, by raising the base level, retention of clastic sediments in the basin. Hot-spring activity produced sinters that are interbedded with the lacustrine sediments, indicating periods of subaerial exposure. The lake eventually drained or dried up, and subsequent sedimentation took place for an unknown period of time in alluvial fans sourced in the surrounding highlands.

Faulting took place largely after sedimentation and produced offset in both the paleohighlands and the basin sediments. Offset along some basin-flanking faults modestly downdropped the basin-filling sediments, but many of the faults with the greatest offset are well within the basin itself and created intra-basin tilted fault blocks, including the east-tilted Schroeder Mountain horst. Thus, faulting was not responsible for most of the present basin configuration. Today, the complex combination of highly variable sedimentary facies and abundant high-angle faults strongly compartmentalizes the ground water in the basin, likely affecting ground water flow and dewatering related to the Gold Quarry mine.

Much of the present configuration of the Carlin basin results from a combination of the pre-sedimentation topography and the effects of Pliocene and younger erosion, as evidenced by more than a dozen down-stepping strath terraces in the basin. Miocene sediments buried much of the older Miocene topography, and later erosion preferentially removed much of the less-resistant sediments and exhumed the older, slightly fault-modified topography cored by more-resistant older rocks. Similar widespread erosion throughout the upper Humboldt River drainage system created strath terraces that connect with those in the Carlin basin. The erosion and downcutting

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took place in response to relative lowering of the early Humboldt River base level in northwestern Nevada. In the latter area, early pediments cut on bedrock have been covered by the sediments eroded from northeastern Nevada. Thus, late Cenozoic erosion in northeastern Nevada, including the Carlin basin, has been exposing older units, whereas same-age sedimentation in northwestern Nevada has been concealing them. This subregional difference in exposure levels affects evaluation of covered areas for mineral exploration, as well as interpretation of basin configurations for ground water resources.

Key Words: Carlin basin, Miocene, Pliocene, Quaternary, sedimentation, faulting, strath terrace, erosion, Humboldt River

INTRODUCTION

Northeastern Nevada contains abundant Cenozoic metallic mineral deposits that formed largely in the late Eocene and middle Miocene. Many studies have focused on how the deposits formed, but few have examined the local to regional processes that took place after mineralization. These processes, including concealment by younger sedimentary and volcanic units, faulting, and exposure or destruction by erosion, locally have had a profound effect on the mineral deposits themselves and complicated exploration for undiscovered deposits. Thus, understanding post-mineralization processes can lead to a better understanding of the geologic and paleogeographic setting at the time of mineralization and the processes that have affected those mineral deposits. In addition, Miocene and younger basins and sediments host important ground water resources in the region. As with the mineral deposits, an evaluation of the origins and histories of these basins and sediments and the evolution of drainage systems can enhance research on and development of water resources in the area.

In order to better understand the effects of late Cenozoic processes, new studies are focusing on the Miocene and younger geologic history in northeastern Nevada. This work focuses on two main time periods: the middle Miocene (roughly 16 to 10 Ma), during which time widespread sedimentary and volcanic units were deposited on the paleosurface, thereby concealing the older landscape, and the Pliocene and younger period of time, during which the evolution and integration of drainage systems has caused considerable erosion of all older units. Some of this work has concentrated on an area near Carlin (Fig. 1), where the products of both the middle Miocene and younger processes can be examined and extrapolated to the

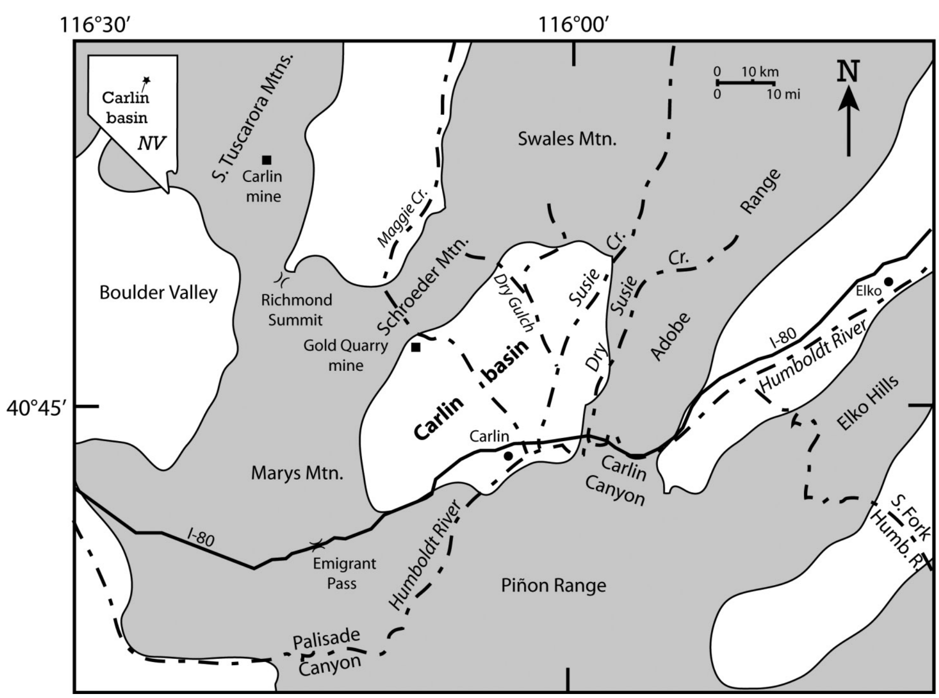


Fig. 1. Locations of the Carlin basin and nearby geographic features, northeastern Nevada. Darker areas are mountain ranges; lighter areas are topographic basins, some of which correspond in part to middle Miocene sedimentary basins. Inset map shows the location of the Carlin basin.

broader area. These studies are in progress, and this short paper briefly summarizes the results of the Carlin-area work and the possible regional implications that have been derived to date.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The physiography of northeastern Nevada, and more specifically the Elko-Carlin area, is dominated by mountain ranges cored by pre-Tertiary sedimentary rocks, local Mesozoic and Tertiary plutons, and a variable cover of Tertiary volcanic and sedimentary rocks. Between these ranges lie broad to narrow valleys and basins that, for the most part, are underlain by Miocene sedimentary rocks. Intermontane Quaternary sediments are far less common than in other parts of Nevada (Stewart and Carlson, 1978), and, in many places, they are present only along modern stream channels. Faults of various ages are present within the ranges; many are pre-Miocene in age, but some formed or were reactivated in the Neogene and Quaternary (Dohrewend et al., 1996).

Various studies on the middle Miocene sedimentary and volcanic rocks in northeastern Nevada indicate that the units were deposited onto a relatively subdued topography (Fig. 2). Most of the volcanism took place between about 16.5 and 14 Ma (John et al., 2000; John, 2001), and sedimentation lasted from about 16.5 Ma to at least 10 Ma (Perkins et al., 1998; Wallace et al., 2004). Mafic to intermediate-composition flows were erupted largely along the north-northwest-trending northern Nevada rift. Rhyolite flows and domes were erupted along or near the rift, as well as along an east-trending band across northeasternmost Nevada where the Jarbidge rhyolite is the principal unit. Topographically low areas began to retain sediments as existing streams were blocked by volcanic flows or faulting, and broad, shallow lakes spread across these lowlands, interfingering in places with contemporaneous volcanic flows. Sedimentation rates exceeded those of basin downwarping in many areas, and the lakes expanded across the lower parts of nearby highlands and merged with lakes in adjacent basins. Significant Miocene faulting was taking place along the Ruby Mountains and East Humboldt Range east of Elko, but faulting in many other areas produced only minor amounts of offset. By about 10 Ma, the resulting landscape had broad, interconnected sedimentary basins, local eroded volcanic edifices, and low-relief highlands cored by pre-Miocene rocks (Fig. 2; Wallace et al., 2004).

CARLIN BASIN—MIDDLE MIOCENE GEOLOGY

The middle Miocene Carlin basin, as reconstructed from its sediments, (Figs. 1, 2, 3) generally was centered over the modern topographic basin near Carlin, but it covered a much larger area. Overall, the Piñon Range to the south, Marys Mountain and Tuscarora Mountains to the west and northwest, Swales Mountain to the north, and the Adobe Range to the east were the limits of the main part of the basin. However, as described below, the basin locally merged with adjacent basins through low areas in the enclosing ranges.

The principal units in the Carlin basin are fluvial and lacustrine sedimentary rocks. The sediments were deposited on Paleozoic and early Tertiary (Eocene to early Oligocene) rocks. Silicic early Paleozoic sedimentary rocks (chert, argillite) are exposed widely in the Marys, Tuscarora, and Swales Mountains areas, and late Paleozoic carbonate and conglomerate units are exposed in the Adobe Range. Rocks of all lithologies are

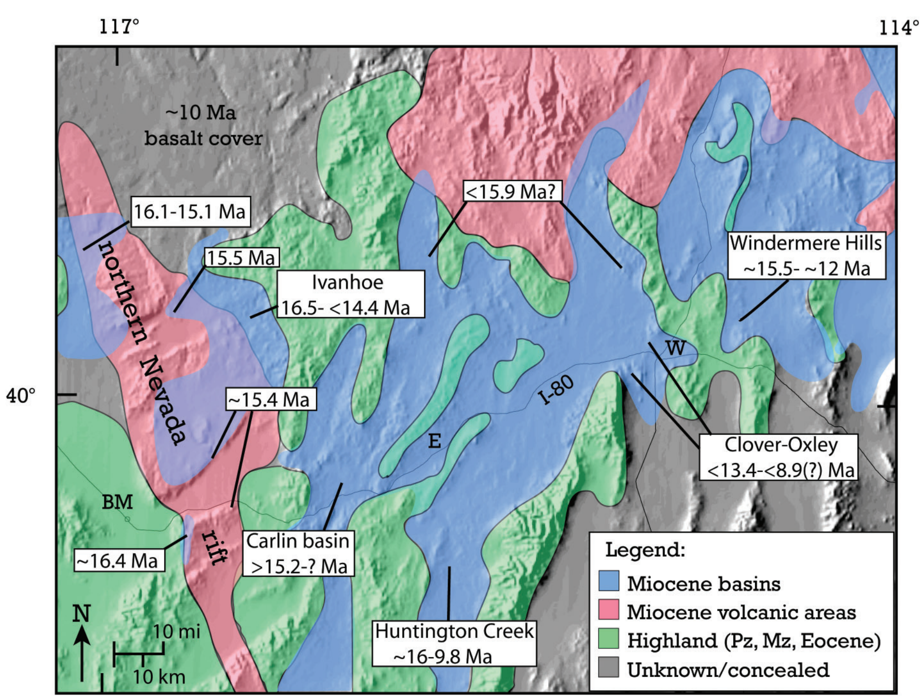


Fig. 2. Schematic map showing the possible middle Miocene paleogeography of northeastern Nevada using the modern physiography as a base. Overlap of some volcanic and sedimentary areas reflects coeval volcanism and sedimentation, or succession of one regime by the other. Many "highlands," which exposed pre-Miocene rocks, had relatively low relief, based on the scarcity of coarse fluvial deposits in the flanking sedimentary sequence. Ages of basin materials include $^{40}Ar/^{39}Ar$ and K-Ar dates on volcanic flow and air-fall ash units and tephra correlations on air-fall ash beds; data were compiled from Snoke et al. (1997), Fleck et al. (1998), Perkins et al. (1998), Mueller et al. (1999), Henry and Faulds (1999), Leavitt et al. (2000), John and Wrucke (2003), Wallace (2003), Thorman et al. (2003), and A. Wallace, R. Fleck, and C. Henry (unpubl. data). BM, Battle Mountain; E, Elko; W, Wells; Interstate 80 shown with light gray line.

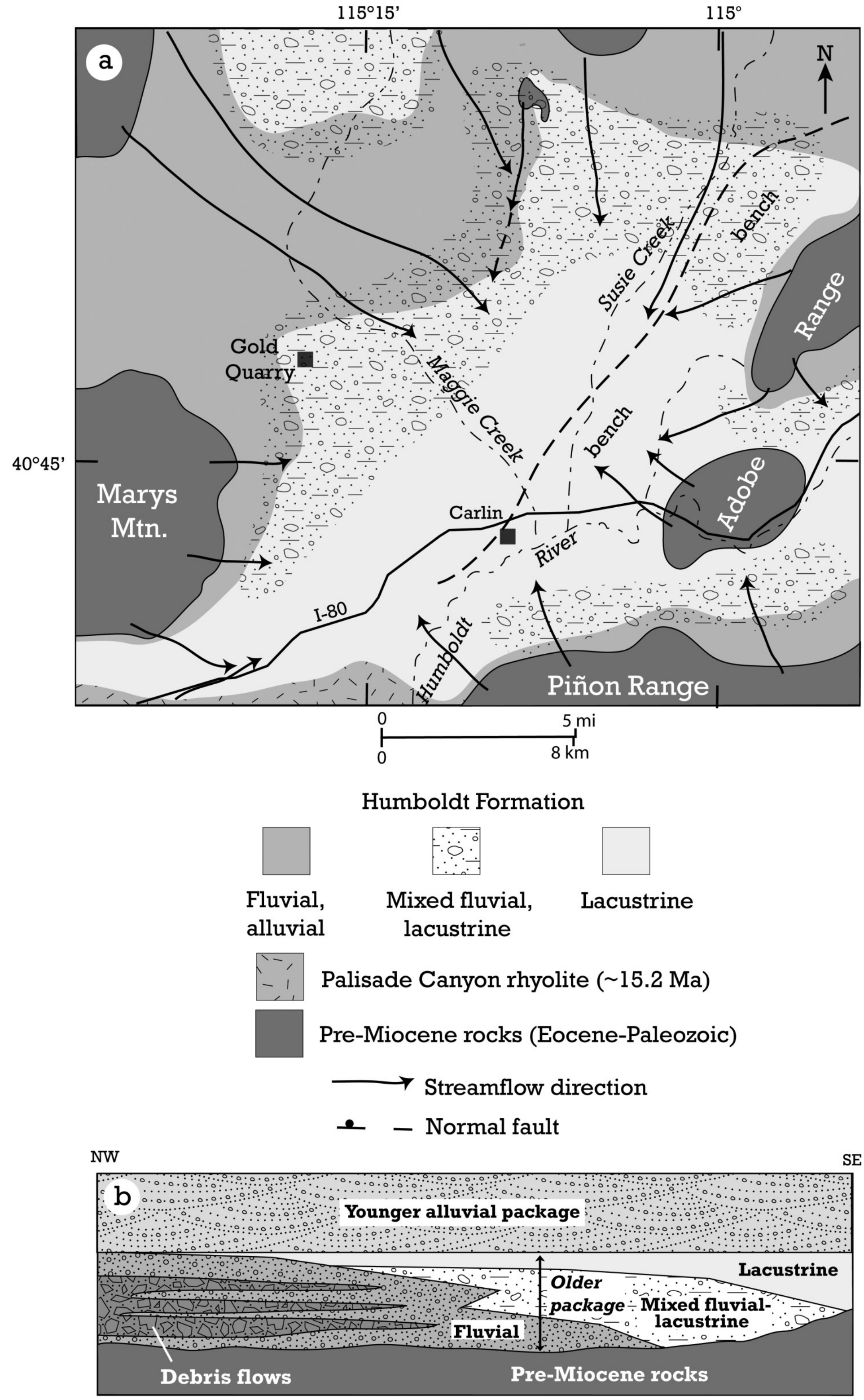


Fig. 3. (a) Map showing the general distribution of the fluvial, lacustrine, and mixed fluvial-lacustrine facies in the older package of the Humboldt Formation. The western limit of a topographic bench east of Susie Creek is shown by a dashed line. Streamflow directions, based on clast imbrications and matching clast lithologies with source area rocks, are shown with arrows. (b) Generalized northwest-southeast stratigraphic section across the northern part of the basin, showing the northwesterly expansion of the lacustrine and mixed environments of the older package, as well as the overlying younger alluvial package of the Humboldt Formation. Dacite flow units exposed in the eastern and southern parts of the basin would be present at the contact between the lacustrine facies and the younger alluvial package.

exposed in the northern Piñon Range. Eocene intermediate-composition and rhyolitic volcanic rocks are widely exposed in the Marys Mountain and Swales Mountain areas, and Eocene rhyolite is exposed locally in the southern Adobe Range. Miocene rhyolite flows underlie most of the basin-filling sediments in the southwestern part of the basin, and dacite flows interfinger with the sedimentary rocks in the eastern and southwestern parts of the basin. Clasts derived from the different basement lithologies were used to reconstruct flow directions during Miocene sedimentation. High-angle normal faults cut all units in the basin area, and all Miocene units are moderately tilted, largely to the east. Limited dates indicate that lacustrine sedimentation was taking place in the southwestern part of the basin at 15.22±0.04 Ma (Henry and Faulds, 1999), but the full age range of basin sedimentation is unknown. $^{40}Ar/^{39}Ar$ dating (R. Fleck) and tephrochronology correlations (M. Perkins) are in progress to establish the life span of the basin and rates of sedimentation.

Miocene Stratigraphy

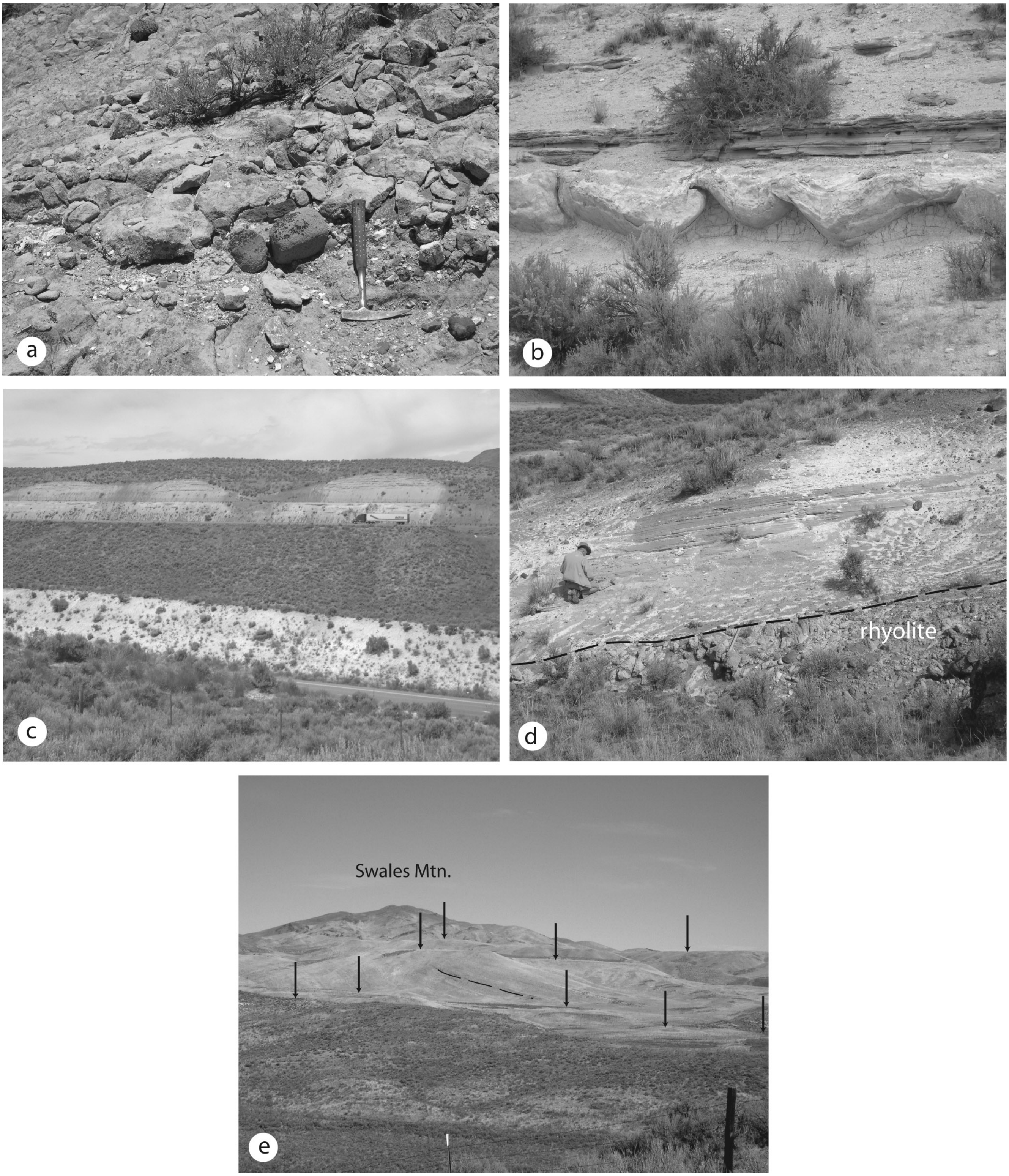
The extensive Miocene sedimentary units in northeastern Nevada are part of the Miocene Humboldt Formation (Sharp, 1939). In the Carlin area, Regnier (1960) subdivided Tertiary sedimentary rocks into several units, including the Raine Ranch and overlying Carlin Formations, and many subsequent papers have used the Carlin Formation name to describe all Miocene sediments along the Carlin trend. Smith and Ketner (1976) demonstrated that the Raine Ranch Formation is Oligocene, and work for the present study (Wallace et al., 2004) indicates that the sedimentary environment that produced the Miocene Carlin Formation extends east over the southern Adobe Range and connects with the type area of the Humboldt Formation defined by Smith and Ketner (1976). On the basis of these regional studies and the original continuity of the depositional environments, the Miocene sedimentary rocks in the Carlin area—Regnier's Carlin Formation—are here included in and called the Humboldt Formation.

In the Carlin basin, the Humboldt Formation has a complex facies architecture that can be divided into two main packages that formed sequentially. The older package is composed of three broad facies—fluvial, lacustrine, and mixed fluvial and lacustrine—that overlapped in time and space (Fig. 3). The fluvial facies is the basal facies in the northwestern and northern parts of the basin (Fig. 3b), and it is composed of sandstone, conglomerate, and debris flow deposits (Fig. 4a). Clast lithologies and clast imbrications indicate derivation from the Tuscarora Mountains, Swales Mountain, Adobe Range, Piñon Range, and Marys Mountain. However, the bulk of the fluvial input was from a southeast-flowing distal fan and braided stream system that sourced in the Tuscarora Mountains, with subsidiary input from the other areas. The clasts in the sediments are composed primarily of Paleozoic silicic rocks and Eocene volcanic rocks, with proportions and specific lithologies depending on source area. These clast lithotypes, coupled with clast imbrication directions and other sedimentary structures, were used to establish flow patterns in the basin. The streams carried varying amounts of ash, which were deposited along with the lithic clasts derived from Paleozoic and Eocene rocks and created a locally ash-rich sand matrix.

The lacustrine facies of the older package consists of fine-grained, ash-rich sediments deposited in a low-energy, shallow lacustrine environment with minor non-volcanic clastic inflow. Soft-sediment deformation is rare but can be pronounced locally (Fig. 4b). This facies forms the basal unit in the eastern and southern parts of the basin (Fig. 3), as well as on topographic highs in the northern parts of the area that were not initially covered by sediments of the fluvial systems. The lacustrine sediments include thinly bedded to massive air-fall ash, locally abundant diatomite, and thin beds of limestone, ash-rich sandstone, and chert. Most of the ash is typical of that produced during Yellowstone hot-spot-related eruptions in northwestern Nevada and southwestern Idaho (Perkins et al., 1998; M. Perkins, oral commun., 2004). Wind ripples marks, mud cracks, hot-spring sinter deposits, and algal mats indicate periodic subaerial exposure. Almost all diatoms are planktonic (predominantly *Aulacoseira granulata*), with minor benthic diatoms near the bases of the sections. Diatomite deposits that formed at the top of the lacustrine section in the southeastern part of the basin were mined in the early 1900s.

Sedimentary rocks in the third facies in the older package are a mixture of the fluvial and lacustrine sedimentary rocks found in the other two facies. Field relations show that, during early basin sedimentation, fluvial sediments were transported to the south and southeast towards and into the lacustrine environment, which was gradually expanding to the northwest. The main fluvial system continued to flow to the southeast as the lake grew, and the mixed-facies environment progressively expanded northwestwardly with time (Fig. 3b). In addition to the hot-spot-related ash beds, this facies contains numerous beds that contain mafic to intermediate-composition air-fall pumice and ash that were both transported by streams or deposited directly on and preserved within the fluvial section. The relative coarseness of these air-fall deposits indicate that they were derived from more proximal sources, such as 15–16 Ma eruptions along the northern Nevada rift (Fig. 2; John et al., 2000).

The younger package of the Humboldt Formation is composed of sandstone, siltstone, conglomerate, and local debris flows that formed in an alluvial-fan to alluvial-slope environment with varying energy levels and source areas. Source areas were similar to those for the fluvial facies of the older package, but the streams that produced the thickest and coarsest preserved deposits of the younger package were derived from the Swales Mountain area to the north. The alluvial sediments become finer grained away from source-area highlands. The contact between sediments of this package and those in the underlying package is conformable (Fig. 4c) and, in most cases, gradational over a meter or less. However, in the southeastern


a
b
c
d
rhyolite
Swales Mtn.
e

part of the basin, the lowest part of the alluvial package contains coarse debris flow deposits derived from the nearby Adobe Range, and these debris flow deposits alternate with finer-grained lacustrine sediments over several tens of meters. Soil horizons and abundant root casts are common in the younger package, but no evidence for a significant time break between the older and younger packages, such as soil horizons or erosion of the older sediments, was found. As exposed along Interstate 80 in the southwestern part of the basin (Figs. 3, 4c), the basal sediments of this package are several tens of meters above the 15.2 Ma Palisade Canyon rhyolite, described below, with an intervening section of fine-grained lacustrine sediments of the older package.

In addition to the abundant air-fall ash in the sedimentary rocks, two Miocene volcanic flow assemblages are present in and near the Carlin basin. In the southwestern part of the basin, eruption of the Palisade Canyon rhyolite (informal usage from Smith and Ketner, 1976; same unit as the rhyolite of Marys Mountain of Henry and Faulds, 1999) produced several hundred meters of flows. The bulk of the flows are southwest of Carlin, roughly between Interstate 80 and Palisade Canyon, and the unit thins to the northeast into the basin. Henry and Faulds (1999) dated the rhyolite at 15.22±0.04 Ma just north of Interstate 80. The rhyolite was erupted during very early lacustrine sedimentation in that area; a thin sequence of sedimentary rocks underlies the flows, but lacustrine sedimentation continued immediately after eruption of the rhyolite (Fig. 4d). No evidence of water-rock interaction, such as phreatic or hyaloclastic breccias, was observed. Thin rhyolite flows are exposed east of Maggie Creek 5 km north of Carlin and may be related to the Palisade Canyon sequence.

Dacite flows were erupted approximately at the same time that sedimentation changed from the older package to the younger package. In most places, the flows were erupted subaerially onto the lacustrine sediments, producing reddish bake zones at the top of the lacustrine sequence, and they were buried by the alluvial sediments of the younger package. The flows were erupted in two areas: in the eastern part of the basin along the west side of and across the top of the modern Adobe Range, and in the southwestern part of the basin a few kilometers north of Carlin. In most areas, only one 2–3-m-thick flow is present, although a second flow is exposed locally in the eastern area. In both areas, the flows appear to have filled very shallow, west- to west-southwest-trending swales. In the western area, the dacite flow unit overlies 1–2 m of lacustrine sediments that were deposited on the rhyolite flows noted above. Sources for the dacite lavas are not evident, although narrow, north-northwest-striking dikes may be present within the eastern flows. The dacite is magnetic, and aeromagnetic data shown in Plume (1995) do not indicate that the flows in the two areas are continuous beneath the upper alluvial package.

The morphology of the pre-sedimentation Carlin basin largely is unknown. Overall, on the basis of paleocurrent flow indicators, the basin floor declined to the south. In a few places, such as along the upper part of Susie Creek and north of Dry Gulch (Fig. 1), small topographic basement highs are surrounded by basal sediments and overlain by younger sediments. Between Susie Creek and the western base of the Adobe Range (Fig. 3), sediments of the fluvial facies and most of the mixed facies are absent and only sediments of the lacustrine facies were deposited above the pre-Miocene basement rocks. At the eastern limit of the fluvial facies, a major, laterally confined stream carried coarse-grained clasts southward along a narrow channel into the basin; the trace of this channel approximates the course of the modern Susie Creek. These stratigraphic relations suggest the syn-sedimentary presence of a topographic bench outboard of the Adobe Range (Fig. 3), the northwestern face of which controlled the location of the stream and restricted eastward extension of the fluvial facies. The origin of this bench is unknown and could have been produced either by a north-northeast-striking, pre-sedimentation fault or by pedimentation related to early, through-going streams. In both the basin as a whole and this area in particular, the older package of sediments shows little or no evidence of syn-sedimentation faulting, indicating that the western edge of the bench formed prior to sedimentation.

Although later faulting and tilting described below modestly offset and deformed the Humboldt Formation, the facies distributions and depositional contacts between the Miocene sediments and older units along the flanks of the basin indicate that the sediments largely filled the pre-sedimentation basin. The Carlin basin depositional environment extended across the low southern end of the Adobe Range highland (Figs. 2, 3) and merged with those in the large sedimentary basin on the east side of the range. Sediments were deposited on the flanks of the ancestral Swales Mountain, Marys Mountain, and the northern Piñon Range, and they originally may have covered

Fig. 4. Sedimentary facies and erosional features in the Carlin basin. (a) Debris-flow deposit in the fluvial facies of the older Humboldt Formation package, north of Dry Gulch. Cobbles composed of Paleozoic and Eocene rocks in a light-gray, ash-rich sand matrix. Hammer for scale. (b) Soft-sediment deformation in sediments of the lacustrine facies of the older sedimentary package along Dry Susie Creek. Convoluted light ash-rich mudstone bed is about 1 m thick and is encapsulated by undeformed, waterlain ash beds. (c) Contact between lacustrine sedimentary rocks of the older sedimentary package (white, below truck) and overlying alluvial sedimentary rocks of the younger package (tan, at and above truck). Looking north across Interstate 80 east of Emigrant Pass. (d) Depositional contact (dashed line) between ash-rich sediments of the lacustrine facies and the Palisade Canyon rhyolite (below line). The top of the rhyolite is a fresh, frothy vitrophyre. Geochronologist for scale. (e) Multiple strath terraces cut into Humboldt Formation sedimentary rocks, north of Dry Gulch on southwest side of Swales Mountain. Arrows point to the more obvious terrace levels; the dip of the Humboldt Formation is shown with a dashed line in the middle of the photography. The elevation difference between the highest terrace in the right background and the modern stream level (arrow at far right side of photograph) is about 200 m. All of the topography between these terrace levels was created by erosion and removal of Humboldt Formation sedimentary rocks.

the area now occupied by Richmond Summit northwest of Gold Quarry (Fig. 1).

The initial development of the lake in the southern part of the basin and the southerly early flow of streams suggest that the streams passed through a Carlin basin "lowland" and were dammed to form the lake. This dam must have been high enough to cause eventual spillage across topographic lows in the surrounding highlands into adjacent basins, although the elevation difference between the basin floor and the lows in the ridgelines likely was less than it is now, due to post-sedimentation faulting. Eruption of the thick sequence of 15.2 Ma Palisade Canyon rhyolite at the southwest end of the basin may have produced a dam that blocked the drainage, although the relative ages of the sedimentary units in the rest of the basin are unknown. Sediments deposited on the rhyolite are lacustrine, with no intervening coarse clastic or soil horizons (Fig. 4d), indicating that, in the area of the eruptions, the lake either began or continued to form immediately after eruption of the rhyolite.

At the other end of the lake cycle, the sudden end to lacustrine sedimentation coincided with the eruption of dacite flows and the onset of alluvial sedimentation, some of it initially coarse-grained, throughout the basin. This abrupt, basin-wide change to clastic sedimentation could have been caused by a sudden increase in precipitation, faulting that caused uplift and disruption of the lake-forming dam, or even simple dam failure related to eruption-related ground motion. Increased precipitation would not explain the disappearance of the lake, and fault-related processes are the more likely causes. Structural evidence for faulting at this time is not readily apparent, although some faults that now cut the upper package of sediments may have begun to form during sedimentation.

Post-sedimentation faulting has disrupted most of the stratigraphic sections, and Late Cenozoic erosion has removed large amounts of the Miocene sediments, especially in the central and southern parts of the basin. Therefore, the original thickness of the Humboldt Formation can be estimated only in a few places. In the northern part of the basin, the older package may have been 900 m thick, with at least 100 m of the younger package overlying it. In the southeastern part of the basin, east of Carlin, the older package was only 100–150 m thick, with perhaps 50 m of the overlying younger package.

Regional gravity data (Fig. 5; Ponce and Morin, 2000) show north-northeast-trending gravity lows in the Carlin basin and in the upper Maggie Creek area (Fig. 5). Modeling of the Carlin

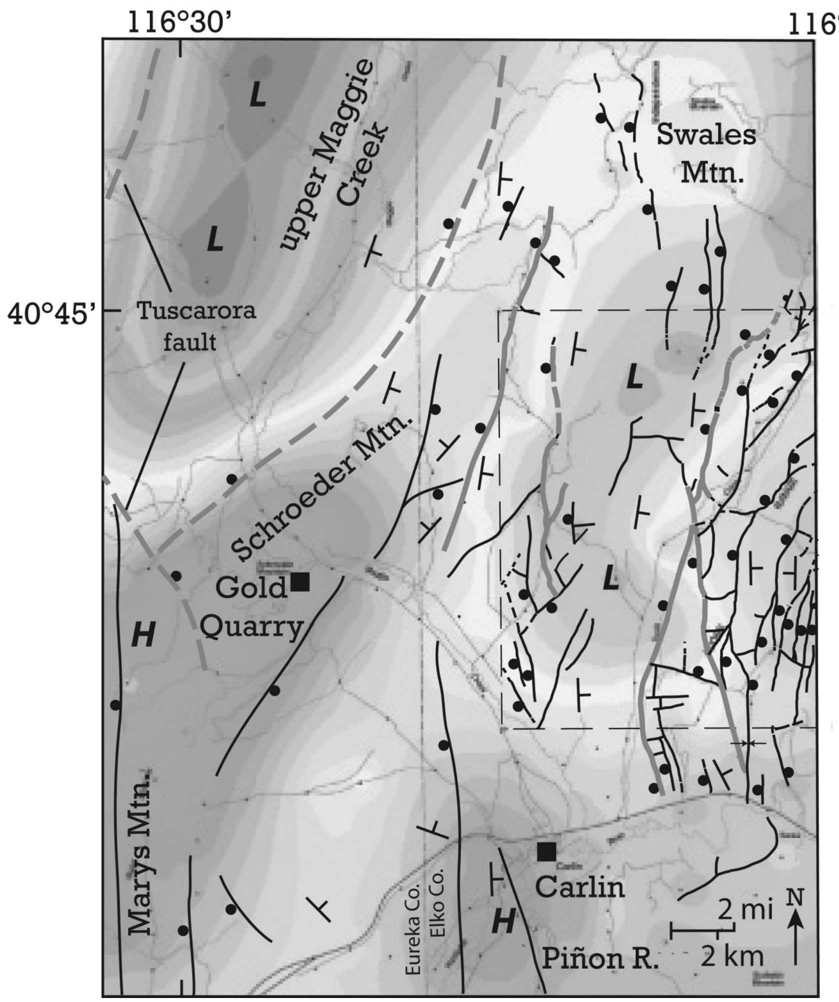


Fig. 5. Isostatic gravity map and faults in the Carlin basin. Gravity lows (L) are interpreted to be areas underlain by relatively lower-density rocks, and gravity highs (H) are areas underlain by relatively higher-density rocks (map from Ponce and Morin, 2000). Superimposed on the gravity map are faults mapped for this study in and around the Huntsman Ranch 7.5′ quadrangle (dashed-line box), as well as major known faults in the western part of the basin; additional faults may be present in other areas, but those areas have not been mapped in detail. Faults with 500 to >1000 m of offset are shown in heavier gray lines; all other faults have tens to 100 m of offset. Ball is on the downthrown side of a fault. The syncline in the southeastern part of the map area was controlled by a fault that had increased offset to the north along strike. Dip symbols show the general orientations of bedding in sedimentary rocks. Also shown are major geographic features, roads, and the town of Carlin. See text for discussion of gravity data.

basin low indicates a depth to basement of about 600 m (D. A. Ponce, written commun., 2004). This low generally corresponds to the area where the reconstructed Miocene stratigraphic section is the thickest, suggesting that this was the axis of the original depocenter. The low also parallels some of the post-sedimentation faults in the basin and thus also may reflect normal offset along those faults. The upper Maggie Creek low (Fig. 5) is pronounced, and modeling indicates a depth to basement of about 1.7 km (D. A. Ponce, written commun., 2004). However, reconnaissance mapping of the various sedimentary facies in that area indicates that the Miocene section is substantially thinner than that, which suggests that other units of similar density lie between the Miocene sedimentary units and the basement. Possible units include the Oligocene Indian Wells Formation, the Eocene Elko Formation, or various rhyolite volcanic rocks exposed to the east on Swales Mountain. The southeast side of the low corresponds to a north-northeast-striking normal fault that displaced units down to the west. This also may have increased the strong gradient on the east side of the low.

Faults and Folds

Although exposures are poor, facies mapping of the Humboldt Formation in the Carlin basin shows the presence of abundant high-angle normal faults, all or most of which appear to post-date sedimentation. Most of the faults strike north-northeast, with a subset that strikes northeast (Fig. 5). Throw along the faults typically is less than a few hundred meters, although throw along a few faults exceeds 1000 m, including two north-northeast-striking faults in the middle of the basin. Except along the west flank of the Adobe Range, where Miocene sedimentary and volcanic rocks dip 10–15° to the west, faulting tilted the Miocene sedimentary rocks to the east, resulting in dips between 5° and 30° and mostly in the 10° to 20° range. Many of the faults in the basin continue northward into the Swales Mountain area, where they offset Eocene and older rocks (Evans and Ketner, 1971). To the south, however, faults appear to die out or diminish towards the northern Piñon Range, but some north-striking, Paleozoic-hosted faults in that area may be continuations of these faults (Smith and Ketner, 1978). The north-northwest-striking Tuscarora fault forms the western and northwestern margin of the basin, dropping the Miocene sediments down to the east by an unknown amount. Near the Gold Quarry mine, northeast-striking faults created the southeast-tilted Schroeder Mountain block, and these faults terminate to the southwest at the Tuscarora fault. On the east side of the basin, between the Adobe Range and Susie Creek, north-striking fault sets have opposite senses of offset on either side of a major, north-northeast-striking fault. To the east, the faults are offset down to the east and formed west-tilted fault blocks; to the west, the faults are offset down to the west and sediments dip to the east. The major fault that separates these sets has only minor offset to the south along Dry Susie Creek, but movement created a synform; along strike to the north, the offset increases and is down to the west.

On the basis of the distributions and offsets of the sedimentary facies, syn- or post-sedimentation faulting did not significantly lower the central part of the basin relative to the flanking highlands. The dacite flows erupted conformably onto lacustrine sediments that originally were horizontal, and they are stratigraphically equivalent at the two areas of exposure; this indicates that topographic relief at the time of eruption was minor. Assuming that the flows in the two areas of exposure were erupted at about the same time, this flow-sediment contact provides a datum. The present difference in elevation of the contact between the crest of the Adobe Range and the middle of the basin is about 260 m. The Humboldt Formation-Palisade Canyon rhyolite contact near Emigrant Pass (Fig. 1) dips northeast and is continuous into the middle of the basin, indicating northeastward tilting of the Marys Mountain area but little or no offset along that part of the basin margin. Thus, although some of the modern topographic relief is due to faulting and tilting, the amount of offset is not enough to explain the modern topographic relief. As described below, some to much of this relief instead is a product of preferential erosion of the less-resistant Humboldt Formation.

CARLIN BASIN—LATE CENOZOIC EROSION

In the Carlin physiographic basin, as many as 16 strath terraces have been identified that cut into the Humboldt Formation and, locally, older rocks (Fig. 4e). Gravel deposits form 1–3-m-thick veneers above a few terraces, but many terraces are strictly erosional and do not have capping gravel deposits. The terraces truncate all Miocene sedimentary units and structures, and no evidence of fault offset of the terraces has been found. The terraces are paired across and stacked above all modern streams, the knickpoints for the terraces become progressively younger downstream to the Humboldt River, and the terrace sequence, with progressively younger ones downstream, continues towards Palisade Canyon (Fig. 1). The younger, lower terraces in the Carlin basin are moderately well preserved and closer to the axis of the modern stream. Erosion has dissected the higher, older terraces, but remnants of these terraces can be traced along the sides of hillslopes on both sides of a drainage to give an indication of the original locations and elevations of the terraces. All terraces in all drainages in the basin are consistent in number and relative elevations regardless of the size of the drainage, be it a major drainage like Susie or Maggie Creek or an intermediate to small subbasin. As most of the drainages in the Carlin basin are related to the south-flowing Susie and Maggie Creeks, the terraces generally increase in number to the south to the Humboldt River. Progressive downcutting also has created new, smaller subbasins that generally increase in number downstream as well.

On the basis of the lower stream terraces, streamflow in the Carlin basin has been to the south during the Quaternary, but the higher terraces suggest an early drainage pattern that was somewhat different than the modern network. Perched coarse stream gravels on the high ridge between Susie and Dry Susie

Creeks (Fig. 1) indicate that early Susie Creek flowed into the Dry Susie Creek drainage, before headward erosion along a proto-Susie Creek eventually captured that stream. Similarly, perched gravel deposits at Richmond Summit (Fig. 1), northwest of the Gold Quarry mine, suggest that the upper part of Maggie Creek originally flowed southwest through that area. Incision, either headward or downward, through the basement-cored Schroeder Mountain near Gold Quarry eventually captured the upper part of Maggie Creek and diverted it to its present southerly course towards the town of Carlin. At Carlin Canyon (Fig. 1), high terraces along the Humboldt River blend with those on the east side of the Carlin basin. The terrace pattern indicates that the river initially flowed northward from the canyon area into the lower Dry Susie Creek area before downcutting establishing the present westward flow. At Carlin Canyon, as well at several other basement-cored blocks along the various drainages, meanders were superimposed onto the bedrock during incision.

Terraces mapped in much of the Humboldt River basin upstream from Carlin match those in the Carlin basin, indicating that erosion in the entire upper Humboldt River drainage has responded to a regional lowering of base level. The only reliable date related to the terraces is from the Elko landfill, where ~2.5 Ma lacustrine sediments were deposited at one terrace level (Reheis et al., 2003). That terrace is one of the lower terraces above the Humboldt River at Elko. This terrace can be traced downstream to the Carlin basin, where it corresponds to one of the intermediate-level terraces in that area. On the basis of this poor age control, terrace formation in the Humboldt River drainage system appears to have begun prior to 2.5 Ma and has continued to the present.

The progressive incision of streams in the Carlin basin has stripped large amounts of Miocene sediments from the basin, and the sediments have been transported out of the area by the Humboldt River. Exactly how much has been removed is unknown, but projection of the highest terraces around the basin towards the Humboldt River suggests that as much as 400 m of downcutting, and thus an equivalent amount of sediment removal, has taken place in the central part of the basin. These amounts are similar to those estimated in other parts of the Humboldt River basin upstream from the Carlin basin. For example, the uppermost terraces near Elko are 390 m above the modern floodplain, and the difference between highest and lowest terraces along the South Fork Humboldt River (Fig. 1) is 380 m.

DISCUSSION

The Carlin sedimentary and topographic basins have a two-part late Cenozoic history: middle Miocene sedimentation and subsequent faulting, and Pliocene (perhaps late Miocene) and younger erosion. During the early constructional phase, filling of sedimentary basins partially to completely buried existing highlands and created a subdued topography with base elevations that were higher than before. Modest to moderate amounts of faulting took place after sedimentation. During the later destructive phase, Humboldt River-related, basin-wide erosion has removed some of the less-resistant Miocene sedimentary rocks and gradually exhumed the pre-middle Miocene highlands. In the Carlin basin and parts of the Humboldt River, many modern streams follow the same paths as their middle Miocene counterparts. Thus, the present topography and some of the drainage systems in large part are similar to the middle Miocene topography and drainages.

The middle Miocene topography likely is a product of Oligocene to early Miocene uplift and erosion. All late Eocene volcanic rocks dip more steeply than overlying Miocene units, indicating a tectonic and possible uplift event between about 36 and 15 Ma. By the middle Miocene, enough erosion of uplifted areas had taken place to expose Eocene plutons and some of the late Eocene Carlin trend gold deposits, both of which shed detritus into the sedimentary basins and locally were buried by the sediments. Thermochronology studies indicate that the Carlin trend gold deposits formed at least 800 m beneath the late Eocene paleosurface on which the Eocene volcanic units were erupted (Hickey et al., 2003). Supergene alunite ages of 18.8±0.2 to 25.9±0.6 Ma from some of the gold deposits (Arehart et al., 1992; Hofstra et al., 1999), as well as apatite fission-track ages that suggest uplift as late as 18–20 Ma (Chakurian et al., 2003; Tosdal et al., 2003), also provide evidence for this Oligocene to early Miocene period of uplift and erosion.

The Late Cenozoic erosion is a product of a regional drop in base level along the Humboldt River, the major throughgoing drainage in northern Nevada. Paleontological and stratigraphic evidence (Repenning et al., 1995; Link et al., 2002) suggests that, from about 6 Ma to 2–3 Ma, the Humboldt River flowed from the western Snake River Plain in southern Idaho, through northern Nevada along its present general course to near Winnemucca, and then flowed westward to the upper tributaries of the Sacramento River. A wide, thick section of stream gravels beneath 4.2 Ma basalt flows near Iron Point east of Golconda indicate that a major throughgoing watercourse was present at that time (Erickson and Marsh, 1974; unpublished industry drilling data). Uplift of the northern Sierra Nevada at about 2–3 Ma (Henry and Perkins, 2001) likely blocked the westward flow of the river, which began to form intermontane lakes in northwestern Nevada (Reheis et al., 2002). At the same time, streamflow in the western Snake River Plain was captured and began to flow into the Snake and Columbia Rivers (Link et al., 2002). Thus, the Humboldt River became isolated at about 2–3 Ma. The only dated terrace in northeastern Nevada formed at about 2.5 Ma (Reheis et al., 2003), which roughly is the same time that the river became isolated. Depending on location, this terrace formed at an intermediate to later stage of downcutting, and the terraces above it likely formed while the river flowed from the Snake River Plain to the Sacramento River. Supergene alunite from the Post Mine, which is along the Carlin gold trend northwest of Carlin, was dated at 9.5±0.2 and 8.6±0.2 Ma (Arehart et al., 1992). These ages are older than the

6 Ma paleontological ages for the Humboldt River reported by Repenning et al. (1995), but they may indicate that enough erosion had taken place by that time to allow supergene processes to affect the Paleozoic-hosted gold deposit.

Strath terraces can form either from uplift of highlands upstream or lowering of downstream reaches, and streamflow variations due to climate changes and related sediment supply can have a significant influence. If the higher terraces in northeastern Nevada formed while the river was connected to the Snake River Plain, the top and bottom of the river system would have been highlands north of the Snake River Plain (Link et al., 2002) and the Pacific Ocean, respectively. Whether either of these two distant locales was changing elevations during this pre-2.5 Ma time, or if changes at either end would have produced the multiple, clear terraces in this distant intermediate region, are unknowns at this point. It is known that, prior to 2.5 Ma, the river flowed downhill to the west.

Since 2.5 Ma, the isolation of the river restricts the base-level-changing influences to northern Nevada. Uplift has been taking place throughout the region since 2.5 Ma (and earlier), but significantly more faulting has occurred in northwestern than in northeastern Nevada. Northwestern Nevada is lower than northeastern Nevada, forming a topographically low region that is clear on digital elevation maps. The Humboldt River crosses the eastern limit of this topographically lower region just east of Battle Mountain, roughly at the transition between more-extended and less-extended domains that formed in the late Cenozoic (Wallace, 1991). Strath terraces are common upstream from this point, and alluvial fans and basin sedimentation are prevalent downstream from this point (Fig. 6), indicating a downstream change from erosional to depositional regimes. On the basis of the present topography, relative amounts of faulting, and geomorphic and sedimentological differences, I suggest that the cause of the declining base level more likely is due to fault-related basin lowering in northwestern Nevada than to uplift of the headwaters region. However, considerably more work needs to be done on this subject, including the roles of climate fluctuations during this period of time.

MINERAL DEPOSIT AND GROUND WATER IMPLICATIONS

The Miocene lakes and sedimentation had two important effects on metallic mineral deposits in the region. The first was to bury some of the older mineral deposits, such as those along the Carlin trend. The second was to act as a host and source of

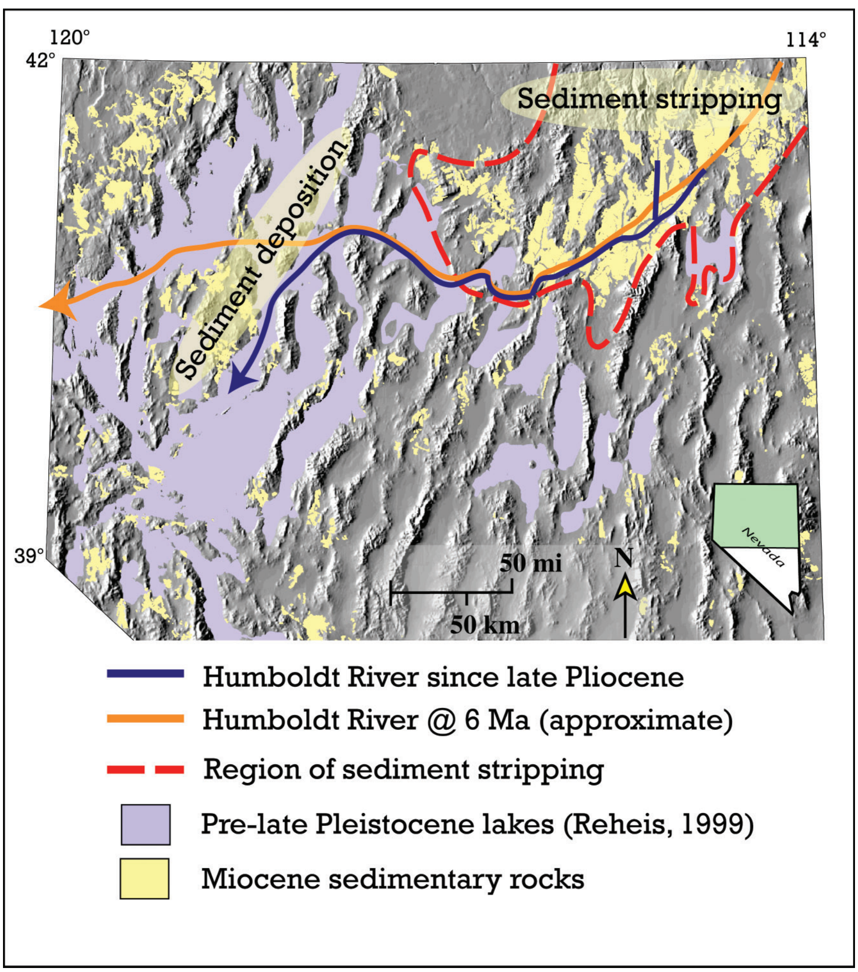


Fig. 6. Shaded relief map of northern Nevada showing the distribution of Miocene sedimentary rocks (yellow; Stewart and Carlson, 1978) and pre-late Pleistocene lakes (blue; Reheis et al., 2002). The interpreted trace of the Humboldt River at about 6 Ma (orange line) is very approximate and based on work for this study and information from Repenning et al. (1995) and Link et al. (2002). The blue line shows the location of the Humboldt River since about 2.5 Ma. The heavy red dashed line in northeastern Nevada outlines the general area where Miocene sediments have been eroded substantially and Quaternary sediments are sparse. Northwestern Nevada in general has been an area of sediment deposition and retention. See text for discussion of the implications of these regional differences on levels of exposure of mineral deposits and on ground water resources.

water for middle Miocene epithermal deposits, as has been shown at the Ivanhoe Hg-Au district, 50 km to the northwest (Fig. 2; Wallace, 2003); sinter deposits in the Carlin basin had a similar genetic link to the sediments and water.

The later erosion had the opposite effect. Removal of the sedimentary host rocks stripped away the shallow parts of epithermal systems, in some cases leaving, depending on depth of erosion, only the feeder zones in underlying rocks. Progressive erosion also partially to completely re-exposed the pre-Miocene mineral deposits, such as at Gold Quarry, reduced the amount of Miocene cover above still-concealed deposits, or produced a thicker oxide zone above a sulfide deposit, perhaps enhancing any effects of pre-middle Miocene exposure and weathering. Therefore, an understanding of the Miocene paleogeography, basin morphologies, and sedimentology, as well as the effects of Pliocene and younger erosion and landscape evolution, is important for mineral deposit exploration in the region.

In northwestern Nevada, along the more downstream, sediment-retentive parts of the Humboldt River system, older deposits, including those formed in the Miocene, progressively have been concealed beneath alluvial fans and the sediments carried downstream from northeastern Nevada. Examples include the middle Miocene-age Sleeper Au deposit northwest of Winnemucca, which was exposed until concealed by late Cenozoic sediments (Wood and Hamilton, 1991); much of the Twin Creeks gold deposit complex, which underlay Pliocene and younger sediments prior to mining (Madden-McGuire et al., 1991); mineralized Paleozoic rocks along the Humboldt River near Iron Point east of Golconda; and the Florida Canyon deposit near Imlay, which is concealed by alluvial fans and cut by Pliocene and younger range-front faults (Thomason, 2002).

As mapped in detail in the Huntsman Ranch quadrangle (Fig. 5), and in general elsewhere in the Carlin basin, the abundant faults strongly compartmentalized the Humboldt Formation and juxtaposed facies with different hydrogeologic characteristics. This compartmentalization likely has a strong effect on ground-water flow in the basin (see Plume, 1995). Flow is from north to south, down hydrologic gradient and parallel to the major faults (Plume, 1995), and the faults may restrict flow in an east-west direction. This flow compartmentalization likely has an effect on some of the dewatering pattern at the Gold Quarry mine on the west side of the basin, perhaps leading in part to the generally north-trending cone of depression around the mine (Maurer et al., 1996), although much of that cone is in the Paleozoic basement rocks. Similar compartmentalization of modern ground water has taken place in the faulted Miocene sediments in the Ivanhoe area (Engle et al., 1998), and it may be an important factor in other Miocene basins in northeastern Nevada.

On a regional scale, the combination of middle Miocene sedimentation and faulting and later erosion created markedly different basins and possible ground water regimes in northeastern and northwestern Nevada. As noted above, fault-compartmentalized Miocene sedimentary rocks may make up the basin fill in many parts of northeastern Nevada. Ground-water flow, and to some degree surface flow, is influenced by these rocks and faults. In contrast, in northwestern Nevada, unconsolidated and relatively unfaulted Pliocene and Quaternary sediments form thin to thick blankets across more consolidated and Miocene basin-filling units, some of which may be faulted. The basin aquifers in that region are a combination of the two sedimentary packages, which likely creates substantial variations in ground-water flow and depths of recharge.

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