The Jackson-Lawton-Bowman Normal Fault System and Its Relationship to Carlin-type Gold Mineralization, Eureka District, Nevada

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ABSTRACT

The Eureka district hosts mid-Cretaceous (~106 Ma), igneous-related, polymetallic carbonate replacement deposits that have subsequently been overprinted by Eocene(?) Carlin-type gold mineralization, including the Archimedes deposit. This study presents (1) results of new Anaconda-style outcrop geologic map of a structurally complex area measuring 4.5 km² in the northern part of the Eureka district along the Jackson-Lawton-Bowman normal fault system, (2) structural reconstructions of Tertiary normal faults, as well as (3) reconnaissance trace-element and stable isotopic analyses in an attempt to differentiate between alteration associated with the mid-Cretaceous and Eocene(?) events. The study evaluates the possible relationship of the Jackson fault system to Carlin-type gold.

The Jackson fault, which has been proposed as a structural control for both styles of mineralization, extends the length of the Eureka district (21 km). The normal fault system dismembers folds of the Eureka culmination, which involves lower Paleozoic carbonate and clastic rocks. Evidence from structural reconstructions suggests that the north-striking Jackson branch and north-northwest striking Lawton branch have dismembered an anticline-syncline pair that is interpreted to have formed by fault-propagation folding concurrent with movement on the Champion thrust fault in the Early Cretaceous in the Eureka portion of the central Nevada thrust belt. Beginning at the southern edge of the district, the Jackson fault zone is composed of a series of overlapping, steeply (~70°) east-dipping, north-striking fault segments for ~3.8 km. Farther north, the main fault splits into at least three closely spaced, roughly parallel branches, which also dip steeply eastward. The Buckeye fault is likely a fourth branch of the Jackson normal fault system.

Contraction and growth of the Eureka culmination occurred concurrent with deposition of the synorogenic Early Cretaceous Newark Canyon Formation at ~116 Ma (Aptian). Mid-Cretaceous intrusions were emplaced and associated carbonate-hosted ores formed at ~106 Ma (Albian, i.e., late Early Cretaceous), or ~10 m.y. after contractional deformation. The fact that the northwest-striking, down-to-the-north Ruby Hill normal fault cuts and offsets mid-Cretaceous mineralization and is in turn cut and offset by the Jackson branch effectively precludes the possibility that the Jackson fault acted as a conduit for mid-Cretaceous magmatic-hydrothermal fluids. Carlin-type mineralization at Archimedes is structurally controlled, but by the older, west-northwest striking, down-to-the-north Blanchard and Molly faults. The Eocene(?) Carlin-type overprint on Cretaceous base-metal mineralization in the northern Eureka district may have enriched the tenor of gold mined from carbonate replacement deposits.

Soil analyses in the northern Eureka district show subtle Au and As anomalies adjacent to the compound portion of the Jackson fault, and the trace of the fault broadly coincides with a belt of carbonate replacement ore mined in the late 1800s,

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which is all or in part of mid-Cretaceous age. Mapped alteration patterns (jasperoid, marble, bleaching, and sanding of carbonates), which spatial relationships and isotopic studies suggest are related to the Cretaceous magmatic-hydrothermal system, nonetheless show no relationship to the Jackson fault. The Jackson-Lawton-Bowman normal fault system postdates and offsets not only the carbonate-hosted ores but also Carlin-type gold mineralization and is likely a mid-Cenozoic fault system. It thus has no genetic relationship to either the mid-Cretaceous or Eocene mineralizing systems but may be responsible for preserving both systems on the eastern side of the area. This study underscores the challenge of identifying structural controls on Carlin-type mineralization prior to or beyond the extent of mining-related exposures, especially in structurally complex areas where there is imperfect exposure and where there may be partial spatial overlap between Carlin-type and other mineralizing systems.

Key Words: Carlin-type gold; carbonate replacement mineralization, structural reconstruction, Eureka district, normal faults

INTRODUCTION

Production from Carlin-type gold deposits in Nevada dominates the United States gold industry (73% of the U.S. total) and has made the state the sixth-largest gold producer in the world (Nevada Bureau of Mines and Geology, 2011). Many Carlin-type deposits, which have been mined since the early 1900s but were first recognized as a new deposit type beginning in the 1960s (Hausen and Kerr, 1968), are now understood to have strong structural as well as stratigraphic controls (e.g., Teal and Jackson, 2002). The genesis of Carlin-type gold deposits has been the subject of much research and debate (Radtke, 1985; Bagby and Berger, 1985; Bakken and Einaudi, 1986; Sillitoe and Bonham, 1990; Seedorff, 1991; Kuehn and Rose, 1992, 1995; Ilchik and Barton, 1997; Stenger et al., 1998; Hofstra and Cline, 2000; Thompson et al., 2002; Emsbo et al., 2003; Cline et al., 2005; Muntean et al., 2011), the bulk of which is devoted to defining and constraining geochemical and thermal conditions at the time of ore formation in order to determine sources of metals, fluids, and heat. Fewer studies have focused on understanding the pre- and syn-mineralization structural controls at the deposit scale (i.e., why some faults are mineralized, whereas others are not; one exception is Yigit et al., 2003). Moreover, published structural reconstructions of Carlin-type deposits are few, despite the fact that post-mineralization faults have undoubtedly dismembered some gold deposits of the Carlin and Battle Mountain-Eureka trends, albeit to a smaller degree than is exhibited by the porphyry centers of the Yerington and Robinson districts (Proffett, 1977; Proffett and Dilles, 1984; Seedorff et al., 1996; Gans et al., 2001). This study describes pre- and post-mineralization structural controls on Carlin-type gold mineralization in the northern Eureka mining district of east-central Nevada and attempts a structural reconstruction of extensional deformation to gain insight into the pre-extensional geometry of the district, following earlier contractional deformation.

The Eureka district is located at the southern terminus of the Cortez or Battle Mountain-Eureka trend (Figure 1). The district has been extensively explored for lead, silver, and zinc since the discovery of rich, gossanous polymetallic carbonate replacement and skarn deposits in 1864 (Hague, 1883, 1892; Curtis, 1884; Binyon, 1946). Like many carbonate replacement deposits (e.g., Tittley, 1993), this mineralization has a clear magmatic-hydrothermal origin, with links to Mo-Cu mineralization, small skarns, quartz and greisen veins in intrusions dated at ~106 Ma (Nolan, 1962; Nolan and Hunt, 1968; Vickre, 1998; Mortensen et al., 2000; Hastings, 2008; Seedorff et al., this volume, a). Carlin-type gold was mined underground at the Windfall deposit as early as 1908. Although Carlin-type ore constituted only a minor portion of historic production, it quickly became the focus of modern exploration in the Eureka district following the discovery of the Archimedes orebody by Homestake in 1993 (Dilles et al., 1996; Russell, 1996; Margoalis, 1997).

The genesis of Carlin-type mineralization is far less certain but is interpreted by some workers as having a non-magmatic hydrothermal origin (Seedorff, 1991; Ilchik and Barton, 1997; Emsbo et al., 2000) and having formed in the late Eocene (Hofstra et al., 1999; Tretbar et al., 2000; Arehart et al., 2003; Cline et al., 2005). Steeply dipping normal faults have been cited as primary or secondary structural controls in a number of Carlin-type deposits (Volk et al., 1996; Teal and Jackson, 2002; Yigit et al., 2003), although the exact nature of the association remains unclear. Deposits are commonly elongate parallel to high-angle faults (Cline et al., 2005), and gold mineralization is commonly localized at structural intersections. Individual deposits are crudely aligned at the regional scale along “trends” up to 150 km in length (Roberts, 1966), leading a number of workers to propose deep crustal structural controls on gold mineralization (Cunningham, 1988; Shawe, 1991; Grauch et al., 1995, 2003; Tosdal et al., 2000).

In the Eureka district, Carlin-type mineralization occurs...
along a pronounced north-south trend (Figure 2), and the gold system is in part superimposed on the mid-Cretaceous carbonate replacement system. Moreover, portions of both mineralizing systems have been affected by supergene alteration and remobilization of materials, which further obscures the temporal relationship between rocks, faults, and hypogene mineralization, as supergene solutions can deposit materials in rocks that were deposited after hypogene mineralization and can fill faults that cut and offset hypogene mineralization. These types of complexities probably contribute to the uncertain—even contradictory—interpretations of the relative ages of events previously reported (e.g., Nolan, 1962; Dilles et al., 1996) and provide a continuing challenge. There has been much speculation as to which high-angle faults may have acted as feeder channels for gold mineralization (Dilles et al., 1996; unpublished Homestake Mining Company reports; unpublished Hamburg Ridge Joint Venture report), but the bulk of it, including the Archimedes deposit and the Windfall, Rustler, and Paroni mines, lies on or parallel to the strike of a complex normal fault zone known as the Jackson-Lawton-Bowman fault system, or the Jackson fault zone. This fault system can be traced from west of the Windfall mine 21 km to the north, where several of its branches
Figure 2. Geologic map of the Eureka district, after Nolan (1962), showing the trace of the Jackson-Lawton-Bowman normal fault system highlighted in blue. Dashed lines represent the inferred trace of the fault under cover. Red circles = Cretaceous carbonate replacement deposits. Yellow circles = Carlin-type gold deposits.

run through the Ruby Hill area and, eventually, the Archimedes pit. The Jackson fault zone has also been suggested as a potential ore control for carbonate replacement mineralization in the district; Nolan (1962) noted that it “coincides with the belt of most intense mineralization in the Eureka district” and “the Jackson zone probably acted as a channelway.”

This study uses an integrated approach to clarify the structure of the northern portion of the Jackson fault zone, where the fault is compound and poorly exposed, with the purpose of attempting to distinguish between alteration products of the Cretaceous event from those of the late Eocene(?) event and to assess the possible significance of the Jackson fault to gold mineralization. A reconnaissance isotopic study indicates that the analyzed materials likely have a magmatic-hydrothermal origin. The integration of result from field mapping, structural analysis, and isotopic study finds no compelling genetic relationship between the Jackson normal fault system and Carlin-type gold mineralization.

METHODS

Lithology, structure, and alteration were mapped at 1:2000 scale over an area of 3 km by 1.5 km along the northern, compound portion of the Jackson-Lawton-Bowman normal fault system using a modified version of the Anaconda mapping method (Einaudi, 1997; Brimhall et al., 2006). This area of 4.5 km² is complexly faulted but offers only fair exposure of outcrops.

The Anaconda method of mapping outcrops uses various color codes for rock type, alteration, veins, ore minerals, and limonites applied to successive overlays. Although the method was originally devised by Anaconda geologists at Butte, Montana, El Salvador, Chile, and Yerington, Nevada, to map igneous rocks and alteration in porphyry environments, it was easily modified to map carbonate rocks. Lithology, veins, faults, and other structures were plotted on a base map. Pervasive alteration (i.e., silicification, sanding of dolomite, etc.) was plotted on a first overlay and oxidation products of ore minerals were plotted on a second overlay.

Several simple and low-cost techniques were employed to supplement field mapping. Soil samples were taken along two east-west transects across the trace of the Jackson fault to identify potential gold anomalies related to fluid flow along the fault. Fourteen surface samples were selected for stable isotopic analysis of carbon and oxygen; calcite and dolomite were sampled from veins and wall rock in altered and unaltered rocks to investigate the nature and isotopic effects of hydrothermal fluids on host rocks and to identify areas of higher fluid flow. Fifteen polished thin sections were examined using a Nikon Eclipse LV100 petrographic microscope in order to better constrain the mineralogy and alteration paragenesis of altered rocks. Newly collected data were integrated with data drawn from existing publications and unpublished internal reports.

A district-scale cross section for the northern part of the Eu-
The geometry of four key faults in the area was determined from structure contours to constrain their true dips and apparent dips in cross section. Stratigraphic separation diagrams were drawn to illustrate changes in the displacement of the Jackson fault zone along its length from the southern boundary of the district to the Archimedes pit, north of which it disappears under cover, and to gain insight into the temporal relationship between the Jackson fault and other structural features. A stepwise reconstruction of a district-scale cross section was attempted to obtain a view of the pre-extensional geometry of the northern Eureka district.

**REGIONAL GEOLOGIC FRAMEWORK**

**Stratigraphy**

The stratigraphic section exposed in the Eureka district consists of a thick section of Early Cambrian to Early Cretaceous carbonate and clastic rocks that have been intruded or overlain by numerous intrusive plugs, stocks, dikes, sills, lava flows, and tuffs ranging from Cretaceous to Oligocene in age (Figure 3). The northern part of the district exposes only the Cambrian and Ordovician part of the stratigraphic section (Figure 4). The characterization provided below summarizes more detailed descriptions by earlier workers (Hague, 1892; Nolan et al., 1956; Nolan, 1962) and emphasizes those units which are demonstrated ore hosts in the Eureka district.

Sedimentary rocks in the district provide a nearly complete record of deposition from the Cambrian through the late Mississippian (Dilles et al., 1996). The lower portion of the section, from the Cambrian Prospect Mountain Quartzite through the Devonian Devils Gate Limestone, is dominated by shelf carbonate rocks inferred to have originally been part of an eastward-thinning wedge of miogeoclinal sedimentary rocks (Nolan et al., 1956). Carbonaceous shales and sandstones are locally interpersed among the limestones and dolostones of the lower Paleozoic section, which host the majority of the mineralization (Figure 4). The Eldorado Dolomite, host to the bulk of the carbonate replacement ores at Ruby Hill and elsewhere, is composed of ~760 m of massive, coarsely crystalline bluish-gray dolomite and limestone. The Eldorado Dolomite is succeeded by the Geddes Limestone, Secret Canyon Shale, and Hamburg Dolomite. The Hamburg Dolomite, host to both carbonate replacement orebodies and to the Carlin-type mineralization at the Windfall, Rustler, and Paroni mines, consists of 300 m of dark gray, massive limestone with dolomite horizons. Although the Hamburg Dolomite occurs roughly 300 m stratigraphically above the Eldorado Dolomite, it is lithologically similar (Nolan, 1962; Hastings, 2008).

Carlin-type gold mineralization at Archimedes occurs in the Cambrian Windfall Formation and the overlying Ordovician Pogonip Group. The Windfall Formation is subdivided into two members: the lower Catlin member, made up of massive limestone with local sandy and silty interbeds and abundant stringers of black chert, and the upper Bullwhacker member, characterized as a tan, platy limestone with shaly/sandy partings (Nolan, 1962). The Pogonip Group includes the basal Goodwin Formation, overlying Ninemile Formation, and uppermost Antelope Valley Formation. The Goodwin Limestone, host to the bulk of gold mineralization at the Archimedes deposit (Dilles et al., 1996), has three members. Shaly and fossiliferous at its base, the Lower Goodwin member (Og1) is best characterized as a medium-grained massive limestone with sparse bedded of chert nodules and fragments (Hastings, 2008). It grades into a thinly (2–10 cm) bedded silty micrite known as the Lower Laminated member (Og1l). This laminated member is in turn overlain by the Upper Goodwin member (Og2), which can be identified on the basis of its medium to thick bedding and conspicuous chert content (locally as high as 20%; Hastings, 2008).

The upper part of the stratigraphic section, beginning in the Mississippian with the Chairmain Shale and Diamond Peak Formation (Nolan, 1962), includes carbonaceous silts, sands, and conglomerates that record the deposition of clastic sediments into a large foreland basin developed along the eastern margin of the Roberts Mountain allochthon during the Antler orogeny (Poole, 1974). Rocks of the Roberts Mountain allochthon are absent in the Eureka district but crop out several kilometers to the northwest (Figure 5). The Pennsylvania-Permian section consists of limestone and conglomerate of the Elly Limestone and Carbon Ridge Formation (Nolan, 1962; Long et al., 2014).

Mesozoic rocks are largely absent in the area but are represented by the Early Cretaceous Newark Canyon Formation (Nolan et al., 1956). The unit consists of conglomerate, mudstone, and limestone that contain fossil fish, ostracods, and nonmarine mollusks (MacNeil, 1939; Fouch et al., 1979). The Newark Canyon Formation is interpreted to have formed in fluvial and lacustrine settings (Vandervoort and Schmitt, 1990). A detrital zircon date from the Upper Conglomerate member yielded a maximum age of 120.7 ± 3.2 Ma, and zircons from a waterlain pyroclastic fall deposit from the Upper Carbonaceous member yield a U-Pb concordia age of 116.1 ± 1.6 Ma (Druschke et al., 2011), indicating that the unit is Aptian (Long et al., 2014). The Newark Canyon Formation has been interpreted as having been deposited in a piggyback basin on the eastern limb of the Eureka culmination as it grew during development of the central Nevada thrust belt at ~116 Ma (Druschke et al., 2011; Long et al., 2014). The age of the Newark Canyon Formation thus indicates that growth of the culmination preceded emplacement of the mid-Cretaceous intrusions and their associated carbonate-hosted ores at ~106 Ma by ~10 m.y.

The district also contains local exposures of a younger conglomerate, with an age bracketed between Late Cretaceous and Eocene (Long et al., 2014).

**Igneous rocks**

Igneous activity in the heart of the Eureka district occurred
Figure 3. Geologic map of the Eureka district, showing the map area (outlined in red) and the branches of the Jackson-Lawton-Bowman normal fault system, after Nolan (1962). Solid blue line represents the main branch of the Jackson fault; dot-dashed lines represent the Jackson and Lawton branches; and the dashed line represents the Jackson/Holly fault. Solid black line is section 104000N.
Figure 4. Stratigraphic column of Cambrian–Ordovician rocks in the Eureka district, with unit descriptions, thicknesses, and the locality of the measured sections from which unit thicknesses were taken.
in at least two discrete periods, mid-Cretaceous and mid-Cenozoic (Blake et al., 1975; Mortensen et al., 2000). In addition, there are Jurassic and Late Cretaceous intrusions nearby. A large Jurassic intrusion crops out ~12 km to the northeast at Whistler Mountain (159.5 ± 3.3 Ma, U-Pb zircon, Mortensen et al., 2000). Late Cretaceous (~86 Ma), strongly peraluminous granitoids are present ~10 km due south at Rocky Canyon and ~12 km to the southwest at McCullough Butte (Barton, 1982, 1987; Long et al., 2014; Barton et al., unpub. data). Although some of the mid-Cenozoic dates originally were regarded as early Oligocene, all of them now are late Eocene considering that the currently accepted age of the Eocene-Oligocene boundary is 33.9 Ma (Walker et al., 2013).

The largest and ostensibly oldest igneous unit in the district is the Graveyard Flat intrusion, which was first intercepted beneath alluvium during the drilling campaign that led to the discovery of Archimedes. Due to intense intermediate argillic and propylitic alteration, the primary mineralogy of the intrusion is uncertain. It consists primarily of quartz and variably altered plagioclase phenocrysts in a fine-grained, equigranular, plagioclase-dominated groundmass (Dilles et al., 1996; Hastings, 2008). Primary ferromagnesian minerals are not preserved; sericite, kaolinite, calcite, chlorite, epidote, and pyrite are common alteration products (Dilles et al., 1996). Textural variations observed by Dilles et al. (1996) suggest that the intrusion may have been emplaced in multiple phases. Mortensen et al. (2000) reported a U-Pb zircon age of 106.2 ± 0.2 Ma for the Graveyard Flat intrusion. The “Archimedes pluton,” which has an imprecise U-Pb zircon age determination of 105 ± 5 Ma (Mortensen et al., 2000), may be related to the Graveyard Flat intrusion.

The Bullwhacker sill occurs west of the Graveyard Flat intrusion. It dips gently east underneath the Archimedes pit and has been interpreted to merge with the Graveyard Flat intrusion at depth. Although the sill was characterized as an “andesite porphyry” by Langlois (1971), it has been strongly sericitically altered; feldspar phenocrysts have been replaced by kaolinite ± sericite ± calcite. Remnant biotite and hornblende phenocrysts occur in less altered samples; quartz phenocrysts are common. The groundmass texture is uncertain, and the relic mineralogy suggests that the rock was most likely granodiorite porphyry. Mortensen et al. (2000) report a U-Pb zircon age of 106.8 ± 1.2 Ma on the Bullwhacker sill.

The Cretaceous Ruby Hill or Mineral Hill stock, a granodiorite, is exposed immediately south of Ruby Hill (Figures 3, 6). Nolan (1962) and Vikre (1998) have attributed carbonate related to emplacement of the Ruby Hill stock. There are numerous preexisting K-Ar ages with scattered results (Table 2 of Vikre, 1998), whereas 40Ar/39Ar dating of igneous biotite and alteration muscovite yields ages of ~105–108 Ma (Vikre, 1998). Mortensen et al. (2000) report a definitive U-Pb zircon age of 106.0 ± 1.6 Ma.

As evident above, the U-Pb zircon ages on mid-Cretaceous intrusive rocks that are interpreted as crystallization ages by Mortensen et al. (2000) are all within error of one another at ~106 Ma, increasing the likelihood that the rocks have a consanguineous origin. The ages of the intrusive rocks correspond to the Albion stage in the lattermost Early Cretaceous epoch (Walker et al., 2013). The intrusions are spatially and temporally associated with carbonate replacement deposits (Nolan, 1962; Langlois, 1971; Vikre, 1998); thus, the age of carbonate replacement mineralization in the district is also ~106 Ma.

A second, younger period of magmatic activity is evident based on radiometric dating of late Eocene extrusive volcanic rocks in the district, which include the Pinto Peak and Target Hill rhyolite flow-dome complexes, the Ratto Springs rhyodacite, and the Richmond Mountain andesite. These were dated by Blake et al. (1975) by K-Ar methods that yielded ages between 37 and 33 Ma. Five 40Ar/39Ar dates from step heating experiments on biotite, hornblende, and plagioclase pheno-

Figure 5. Simplified tectonic map of Nevada, showing locations of major Paleozoic (Roberts Mountain and Golconda) and Mesozoic (Luning-Fencemaker, central Nevada, and Sevier) thrust systems, as well as Cordilleran metamorphic core complexes (solid black). Belts of Carlin-type gold deposits shown in gray. Box outlines limit of Figure 1. Based on Clive et al. (2005) and Long et al. (2012).
crysts by Long et al. (2014) yield the plateau ages that range from 37.43 to 37.14 Ma, with 2σ errors ranging from 0.02 to 0.21 Ma. In addition, a single-crystal 40Ar/39Ar sanidine date on rhyolite lava from the Pinto Peak dome yields an age of 36.69 ± 0.04 Ma (Long et al., 2014). Late Eocene volcanic rocks overlie Carlin-type gold ore hosted by Paleozoic rocks at both the Rustler and East Archimedes pits, implying shallow depths of gold deposition and perhaps constraining their ages (C.D. Henry, written commun., 2014; Barton et al., unpub. data). The implications of radiometric dates on volcanic rocks for the age of Carlin-type ores remains problematic in some cases because it remains to be determined whether anomalous metal contents and clay alteration in the volcanic rocks are of hypogene or supergene origin (C.D. Henry, written commun., 2014; Barton et al., 2015). At this time, the most likely age of the Carlin-type gold deposits in the district is 36–38 Ma, i.e., late Eocene by the time scale of Walker et al. (2013).

**Geologic structure**

Hague (1892) divided the Eureka district into structural blocks, the dominant features of which are large, roughly north-south trending, fault-bounded antiforms. The most well known of these is now referred to as the Eureka culmination, in which the oldest rocks in the stratigraphic section (Cambrian Prospect Mountain Quartzite) sit at the highest elevation in the district on Prospect Peak, surrounded by younger strata at lower elevations (Figure 3). Later workers (Nolan, 1962; Nolan et al., 1971; Nolan et al., 1974) mapped folds and thrust faults within these blocks, including the Hoosac fault, which has since been interpreted by various workers as either a thrust fault (Taylor et al., 1993; Lisenbee et al., 1995; Long, 2012) or a normal fault (Hague, 1883; Nolan et al., 1974; Long et al., 2014; this study).

Considering that the Eureka district is located just kilometers from the easternmost exposures of the Roberts Mountains allochthon (Dilles et al., 1996), contractional deformation in the district, lacking other constraints, might be attributed to the emplacement of the allochthon in the mid-Paleozoic (Figure 5). Orogenic deposits of Early Cretaceous age, however, have been tied to contractual deformation in the Eureka district. Conglomerates of the Newark Canyon Formation (Vandervoort and Schmidt, 1990) yield U-Pb zircon ages of 116–121 Ma (Druschke et al., 2011; Long et al., 2014). Although the presence of some mid-Paleozoic deformation probably cannot be precluded, the thrust faults that were originally described by Nolan (1962) subsequently have been grouped into the Eureka thrust belt, were later correlated with the Garden Valley thrust system, have become part of what is now known as the central Nevada thrust belt (Figure 5), which in turn has been tied to the Sevier orogeny (Speed, 1983; Speed et al., 1988; Bart-
ley and Gleason, 1990; Armstrong and Bartley, 1993; Taylor et al., 1993, 2000; Druschke et al., 2011; Long et al., 2014). As emphasized by Bartley and Gleason (1990), the present-day distance between the central Nevada thrust belt and the Sevier thrust front of ~350 km (Figure 5) is substantially greater than the Cretaceous distance, which was probably ~200 km (e.g., Gans, 1987), because of subsequent extensional deformation.

The kinematic history of the Sevier fold-and-thrust belt (Armstrong, 1968) in the type area of western Utah during the Early Cretaceous has been a matter of debate (e.g., Armstrong, 1968; Wiltschko and Dorr, 1983; Heller et al., 1986; DeCelles, 2004). Conglomeratic fluvial deposits of the Kelvin, Cedar Mountain, and San Pitch Formations in Utah and the Gannett Group in Wyoming, which are Lower Cretaceous (Katich, 1951; Stokes, 1952; Simmons, 1957; Thayn, 1973; Kirkland, 1992; Tschudy et al., 1984; Witkind et al., 1986; Weiss et al., 2003; DeCelles and Burden, 1992), have characteristics of typical foredeep deposits (DeCelles and Currie, 1996) and were sourced from the south-west (Furer, 1970; Lawton, 1982, 1985; DeCelles, 1986; DeCelles and Burden, 1992; DeCelles et al., 1993; Lawton et al., 1997; Mitra, 1997; Currie, 1997, 2002). These data suggest that initial displacement on thrusts of the classic Sevier belt in Utah had begun by Early Cretaceous (DeCelles and Coogan, 2006). Aptian deformation within the Eureka district in the hinterland of the Sevier thrust belt is coeval with emplacement of the Canyon Range thrust in western Utah but postdates initiation of the Sevier belt in western Utah by 10–30 m.y. and thus represents out-of-sequence deformation (Long et al., 2014).

The ages of deformation suggest that the type Sevier thrust belt and the central Nevada thrust belt systems overlapped in time and thus may be kinematically linked. There is evidence in the Snake Range of eastern White Pine County for contractional deformation of mid-Jurassic and Late Cretaceous ages (Miller et al., 1988), but the ages of rocks that crop out at the base of the early Cenozoic unconformity and the uniformly low Conodont Alteration Indices (CAI) for a given stratigraphic horizon indicate that most of east-central Nevada was not breached by major thrust faults and thus was a relatively undeformed area in the hinterland of the type Sevier belt in Utah and southern Nevada (Armstrong, 1968; Gans and Miller, 1983; Gans et al., 1990; Long, 2012). The thrust systems in central Nevada and western Utah instead could be largely separate, west-rooted thrust systems that eventually merge to the south near Las Vegas (Figure 5). Alternatively, they could be kinematically linked by a large, bedding-parallel flat that passes beneath east-central Nevada (e.g., Figure 22-15 of Speed et al., 1988).

The challenge in this study is to attempt to decipher the nature and relative ages of various structures in the northern Eureka district, given that (1) some contractual structures might be mid-Paleozoic in age and some are almost certainly Early Cretaceous in age, (2) at least small-scale structures might be associated with emplacement of the late Early Cretaceous Ruby Hill stock broadly synchronous with deposition of base metas during carbonate replacement mineralization, and (3) there surely are one or more generations of extensional faults in the district, before, concurrent with, or after Carlin-type gold mineralization, and various episodes of supergene weathering.

Pre-Cenozoic structural relief

Several lines of evidence suggest that the Eureka district was an area of locally significant topographic relief prior to the initiation of Basin and Range-style extension. A recent Paleogene paleogeologic or subcrop map (Long, 2012) indicates that the area between the northern Pancake Range and Eureka has undergone 3–6 km of exhumation since the late Eocene; calculated exhumation values decrease to ~2 km north of Eureka. Stable isotope paleoaltimetric analyses have returned δ18O values as negative as −14 to −16 per mil from calcite in the limestones of the Cretaceous Newark Canyon Formation from its type locality in Newark Canyon (J. Quade, pers. commun., 2013; Snell et al., 2014), which correspond to a minimum elevation of 2–3 km. The Newark Canyon values are corroborated by isotopic data from the distal, meteoric water parts of the 86 Ma McCullough Butte hydrothermal system that yield δD ~ −100 permil equivalent to −14 permil δ18O (Barton et al., 2015). Thermal alteration index (TAI) values from amorphous kerogen in carbonate rocks of the Windfall Formation and Pogonip Group range from 3 to 4+, indicating that paleotemperatures in these rocks ranged from ~65 to 120°C (Home-stake Mining Company unpublished report; Staplin, 1977; Dutton, 1980). Assuming a typical geothermal gradient of 25°C/km, TAI values of 3–4+ indicate 2.6–4.8 km of burial.

Such data suggest that the Eureka district was an area of significant relief by the Early Cretaceous. However, as noted by Long et al. (2014), timing of contractual structures in the district remains poorly constrained due to varying interpretations of individual features and overprinting by complex extensional structures, including the Jackson-Lawton-Bowman fault system.

RESULTS

Lithology and structure

A generalized geologic map of the Eureka district is presented in Figure 7 that highlights the locations of the major faults and the district-scale cross section. A new 1:2000-scale Anaconda-style outcrop geologic map of an area of 4.5 km² was made along the Jackson-Lawton-Bowman fault zone (Figures 8–11), extending along the fault from the historic workings at Ruby Hill for 3 km south to east of the Sterling tunnel. Rock types and lithology are shown in Figures 8 and 10. Structure contour maps also were generated for the major faults in the map area (Figure 12).

The geology of the northern Eureka district is described here in terms of the district’s major structural features, which
strike either roughly north-south (the Sharp fault, the Eureka culmination, the Jackson-Lawton-Bowman fault zone, and the Hoosac fault), northwest-southeast (the Ruby Hill fault), or northeast-southwest (the Silver Connor fault). The Sharp and Hoosac faults lie outside the area of 1:2000 scale mapping for this study but are included in a 4-km transect for construction of a district-scale cross section (Figure 6) that is used for a subsequent structural reconstruction.

\textit{Sharp fault}

The Sharp fault is the intermediate member of a set of three, northwest-stepping, west-dipping normal faults that define the Eureka district’s western edge (Figures 6, 7). From south to north, the set consists of the Cave Canyon, Sharp, and Spring Valley faults (Nolan, 1962). These faults cut alluvium and are interpreted by most workers (e.g., Nolan, 1962) to be related to Basin and Range-age extension, although there are other northerly striking, west-dipping normal faults in the footwall of the Cave Canyon fault that probably are older (e.g., Dugout fault of Nolan, 1962) and that contain Au- and Sb-bearing jasperoid. There are other west-dipping faults in the district, including at least one small-displacement fault in the Archimedes deposit (Dilles et al., 1996).

The Sharp fault is poorly exposed over much of its trace, but Nolan (1962, p. 25) reported dips of 55–60°, and his map shows that the fault has a northern tip with several splays that dip 48–72°W. On the cross section (Figure 6), the Sharp fault is shown with an apparent dip of −64°. The Sharp fault places Devonian Devils Gate Limestone in the floor of Spring Valley against the Lower Cambrian rocks that make up the western flank of the Eureka culmination on Prospect Ridge and Mineral Hill. The Devils Gate Limestone in eastern Spring Valley adjacent to the Sharp fault is thick-bedded and somewhat poorly exposed. The Cambrian Prospect Mountain Quartzite and El-
Figure 8. Anaconda-style outcrop map of the northern Jackson fault zone showing lithology, structure, and veins.
Figure 9. Anaconda-style outcrop map of the northern Jackson fault zone showing alteration.
dorado Dolomite on the western flank of the culmination strike roughly north-south and have moderate to steep westerly dips (35–60°).

**Eureka culmination and the Champion fault**

The Eureka culmination is a well-defined, north-south trending anticlinal crest that includes Prospect Ridge and Mineral Hill and that is marked by extensive exposures of Cambrian Prospect Mountain Quartzite (Figure 3, 7); it is a regional structure with a strike length of ~100 km, the existence of which has been corroborated by Paleogene erosion patterns (Long, 2012; Long et al., 2014). In the Mineral Hill area in the northern Eureka district, folds have been dismembered by crosscutting normal faults (Figure 6), and the map pattern of the culmination consists of a core of Cambrian carbonate rocks, which are flanked to the east and west by the Lower Cambrian

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**Figure 10. Anaconda-style outcrop map of the southern Jackson fault zone showing lithology, structure, and veins.**
Prospect Mountain Quartzite (Figure 7). The carbonate rocks in the core are folded into a syncline with the stratigraphically youngest Hamburg Dolomite in the center and stratigraphically oldest Eldorado Dolomite defining the edges (Figure 6). Folding appears to be spatially associated with the Champion fault, a west-dipping reverse fault (Figures 6, 7). Structure contours on the Champion fault indicate that it dips 23° to 43°W, steepening from south to north.

Moving from the western edge of the cross section toward the center of the fold, the dips of the rocks over a short distance roll over from shallow easterly dips, through near-vertical dips, to overturned, moderate westerly dips in the core of Hamburg Dolomite (Figure 6). Thus, the western limb of this dismembered syncline, referred to in this study as the Mineral Hill syncline, is overturned. The Cambrian Prospect Mountain Quartzite on the western flank of the Mineral Hill syncline dips

Figure 11. Anaconda-style outcrop map of the southern Jackson fault zone showing alteration.
Figure 12. Structure contours on selected normal faults in the northern Eureka district. (a) Champion fault; (b) Buckeye fault; (c) Jackson fault; and (d) Lawton fault. The north-south grid lines are spaced 2 km apart.
moderately steeply (55–60°) to the west. The Prospect Mountain Quartzite on the eastern flank of the syncline is intensely fractured and oxidized; no reliable bedding surfaces have been identified during this or any previous studies.

**Jackson-Lawton-Bowman normal fault system**

The Jackson-Lawton-Bowman normal fault system runs the length of the Eureka district. It is mapped as a single fault strand from the southern edge of the district north to the Eureka tunnel, at which point the strand diverges into the Jackson and Lawton branches (Figures 3, 7). Due to its tendency to form topographic depressions, the fault is poorly exposed along its length and has been identified primarily on the juxtaposition of younger units in the hanging wall (down to the east) against older units on Prospect Ridge and Mineral Hill. Just south of the map area of this study Nolan (1962) recorded steep easterly dips of 70–72° on the fault. At the southern end of the map area, the northern continuation of the Jackson fault splits into two branches; the Jackson branch continues to the north, and the Lawton branch (Zulu Canyon fault of Vikre, 1998) veers slightly to the northeast along the floor of Zulu Canyon. Structure contours on the Jackson branch indicate dips that range from ~23° to 36°E, with an apparent dip in the cross section of 27°E (Figure 12c), similar to the dip shown on the cross section (Figure 6). Structure contours on the Lawton branch indicate that the southern end dips at ~40°E, whereas the northern end dips at only ~12°E, with an apparent dip in the cross section of 20°E (Figure 12d). The hanging wall of the Jackson branch consists of a continuous panel of Cambrian–Ordovician carbonate and clastic rocks that dip to the east; dips are steepest close to the fault and gradually shallow to the east. The footwall of the Jackson branch consists of intensely fractured and oxidized Cambrian Prospect Mountain Quartzite, which dips moderately to the east. The Lawton branch contains west-dipping Secret Canyon Shale, Geddes Limestone, and Eldorado Dolomite in the hanging wall; in its footwall is the Hamburg Dolomite, which makes up the core of the Mineral Hill syncline.

**Buckeye fault**

Between the Lawton branch to the west and the Jackson branch to the east is a third structure, the Buckeye fault (Figure 6), which has historically been interpreted as the roof thrust of a duplex known as the Ruby Hill thrust zone. The Buckeye fault juxtaposes the east-dipping Prospect Mountain Quartzite in the footwall of the Jackson branch against the moderately west-dipping Secret Canyon, Geddes, and Eldorado units in the hanging wall of the Lawton branch. Close examination of the map pattern shows that this fault cuts down section and thus is more likely a fourth branch of the Jackson normal fault system. At its southern end, the Buckeye fault has a dip of 25°NE measured in outcrop. Structure contours on the fault indicate that it has a true dip of ~20–25° to the east or northeast, with an apparent dip of ~16°E in the cross section (Figure 12b), which is similar to the dip shown on the cross section (Figure 6).

**Hoosac fault**

The Hoosac fault is perhaps the most controversial structure in the Eureka district. Originally described by Hague (1883), its trace is currently mapped from Hoosac Mountain at the southern boundary of the district north through the town of Eureka. The fault is buried by lava flows and tuffs or alluvium for almost its entire length. The one exception is on Hoosac Mountain, where it was first described. Thus, its interpreted trace north of the mountain is based on the estimated location of juxtaposed rocks of the Ordovician Hanson Creek Formation and Permian Carbon Ridge Formation. The Hoosac fault has been interpreted as both a contractual feature (Nolan, 1962; Taylor et al., 1993; Lisenbee et al., 1995) and an extensional feature (Hague, 1883; Nolan et al., 1974; Long et al., 2014). Hoosac Mountain is outside the map area for this study, but the Hoosac fault is critical to district-scale structural reconstructions. The apparent dip shown in the cross section of Figure 6 is 60°E.

**Ruby Hill fault**

The Ruby Hill fault is a northwest-striking structure that forms the northeastern boundary of Ruby Hill (Nolan, 1962). Nolan (1962) shows three dip measurements on the northeastern side of Ruby Hill, from north to south, of 70°, 62°, and 60°NE. The fault drops Cambrian Hamburg Dolomite in the hanging wall against Cambrian Eldorado Dolomite in the footwall, omitting at least 300 m of stratigraphic section and offsetting Cretaceous carbonate replacement mineralization. The Eureka Corporation sunk the FAD shaft 1941 in order to exploit mineralization in the hanging wall of the Ruby Hill fault but, famously, was forced to abandon the project after encountering high volumes of groundwater when the shaft pierced another fault, the Martin fault, which parallels the Ruby Hill fault (e.g., Nolan and Hunt, 1968). As the Ruby Hill fault continues to the southeast, it is cut and offset ~400 m to the south by the Jackson branch. This timing relationship (i.e., the Ruby Hill fault cutting mid-Cretaceous mineralization and, in turn, being cut by the Jackson fault) is one of the few broad constraints on the age of the Jackson fault system.

**Silver Connor fault**

The Silver Connor fault, which is well exposed on Prospect Ridge, strikes N40°E and dips ~80°SE. Like the Ruby Hill fault, it juxtaposes the Hamburg Dolomite against the Eldorado Dolomite; however, the Ruby Hill fault is down to the northeast and the Silver Connor fault is down to the southeast. The Silver Connor fault also appears to be cut by the Jackson fault to the northeast, where the Jackson and Lawton branches come together; however, exposure is poor and the offset portion of the Silver Connor fault could not be found east of this intersection.

**Alteration types and distribution**

Figures 9 and 11 show the distribution of alteration in the
map area, which falls into four broad categories: silicification, marble and hornfels, bleaching, and sanding.

**Silicification**

Silicification, or the replacement of carbonate minerals with silica, is a common alteration type in Carlin-type deposits but also occurs in a variety of other hydrothermal systems (Lovering, 1962). In the Eureka district, silicification is found in various forms: (1) as true “jasperoid,” the total replacement of a carbonate rock outcrop with silica, (2) as “nodular” jasperoid, or the partial replacement of carbonate rock with silica in seemingly irregular patches, (3) as jasperoid veins, which can be centimeters to tens of centimeters thick and tend to be strongly oxidized (Figure 13a); and (4) as “spiderweb silica,” or thin, randomly-oriented veinlets of silica cutting across otherwise unaltered carbonate rock (Figure 13b).

In the Eureka district, jasperoid may be hematite-bearing or hematite-absent. Hematitic jasperoid tends to be intensely brecciated; small (mm to cm scale), highly angular, silicified clasts make up ~75–80% of the rock and are chaotically distributed in an equally siliceous matrix. In thin section, complex crosscutting relationships are observed. Multiple generations of tiny silica veinlets crosscut the rocks; in some cases, silica veinlets are terminated at clast boundaries, whereas in other cases the veinlets cut both clast and matrix, suggesting that silica was continually flooding the rock as it was being brecciated (Figure 14). Non-hematitic jasperoid is equally well silicified but is dark gray and exhibits no brecciation, although any primary depositional textures that may have been present are destroyed.

Figures 9 and 11 show the distribution of alteration types in the map area. Hematitic jasperoid (including spiderweb silica, jasperoid veins, and nodular jasperoid as well as massive jasperoid) is the dominant type; non-hematitic jasperoid was found only as float on a historic mine dump in the Cambrian Hamburg Dolomite near the Hamburg–Dunderberg contact. Hematitic jasperoid, by contrast, is common in the northern part of the district, where it is best developed on Mineral Hill, and in the limestone of the Ordovician Pogonip Group east of the historic Jackson mine. Map patterns show that hematitic jasperoid is gradational in intensity. Narrow, elongate cores of massive brecciated jasperoid outcrop are surrounded by wider zones of nodular jasperoid, which are in turn surrounded by a zone of jasperoid veins; most distal to the core is a zone of spiderweb silica.

**Marble and hornfels**

Marble in the Eureka district consists of coarse- to very coarse-grained, recrystallized calcite. It may be bleached white or retain the gray to blue-gray color of the original unrecrystallized carbonate rock. In general, the coarsest textures of marble occur where the rock is also bleached. Spatially, the distribution of marble is limited to the Hamburg Dolomite west of the Lawton branch on Mineral Hill, where it is abundant; the presence of marble in this area can be attributed to heating by intrusion of the Mineral Hill stock.
ble on Mineral Hill by the Lawton branch. However, porphyritic dike material (10–15% hornblende and ~20% plagioclase phenocrysts in a dark gray, aphanitic groundmass) can be found locally in float on the eastern wall of the canyon. The hornfels observed in the Secret Canyon Formation may be related to the intrusion of this dike.

**Bleaching**

Bleaching of carbonates is common in the Eureka district, as discrete patches or elongate fingers. In the northern part of the map area, bleaching of marble occurs on the southern end of Mineral Hill; bleached marble appears to grade out into unbleached marble and eventually into unaltered carbonate rock. In the northern map area, patches of bleached rock also trend northeast-southwest through the Hamburg Dolomite, the Windfall Formation, and the Pogonip Group, coinciding with the trace of the Ruby Hill fault. In the southern part of the map area, bleaching is prominent in the Hamburg Dolomite, where it essentially demarcates the fault contact between the Hamburg and Eldorado Dolomites (Figures 9, 11). Perhaps more than any other alteration type, bleaching appears to be fault-controlled; it is often, but not always, spatially associated with jasperoid.

**Sanding**

Sanding of dolomite is important in the Eureka district. Sanding is spectacularly exposed in the Hamburg Dolomite at the Paroni, Rustler, and Windfall pits, where Carlin-type gold was mined along the Hamburg–Dunderberg contact, and, therefore, appears to be important to the development of Carlin-type deposits in the district. In his description of this alteration in the Hamburg Dolomite, Nolan noted that the “hard dense rock that is normally characteristic of the Hamburg has been converted to a dolomite ‘sand,’ which can be easily scraped and broken by a pick, although it is sufficiently compact to maintain nearly vertical walls” (Nolan, 1962, p. 44). The conversion of “hard dense rock” to dolomitic sand seems to be the result of hydrothermal fluids dissolving interstitial calcium carbonate that cements dolomite grains, because unsanded Hamburg Dolomite commonly reacts vigorously with hydrochloric acid but sanded Hamburg Dolomite does not. The areal extent of sanding in the map area is small; it occurs only as small, discrete patches in the Hamburg Dolomite west of the Jackson branch and also in the Hamburg Dolomite on Mineral Hill.

**Geochemical analyses**

**Whole-rock trace-element analysis of jasperoid**

Three surface samples of jasperoid were submitted for whole-rock analysis using the complete package analysis of ALS Labs (includes 14 lithophile elements by lithium metaborate fusion, X-ray fluorescence, or ICP-AES and 31 elements by lithium borate fusion and ICP-MS). The samples were also analyzed for gold.

Non-hematitic jasperoid samples SC-001a and SC-001b were collected from a mine dump in the Hamburg Dolomite on the northeastern flank of Hamburg Canyon, at the contact between the Hamburg Dolomite and Dunderberg Shale. This is the only locality in the map area where non-hematitic jasperoid was observed. Farther south in the district, the Hamburg–Dunderberg contact is host to Carlin-type mineralization at the Paroni, Windfall, and Rustler mines. Scorodite, a common secondary mineral resulting from the oxidation of arsenic-bearing minerals, was observed on fracture surfaces. Sample SC-002 was collected from a brecciated, hematitic jasperoid outcrop in the Ordovician Goodwin Limestone just east of Austin Canyon, an area that was considered to be one of the most prospective for Carlin-type mineralization based on lithology, abundant silification, apparent structural ground preparation (due to its proximity of the intersection of the Jackson branch with the Ruby Hill fault), arsenic and gold anomalies in historic soil samples, and a paucity of historic drilling.

Table 1 shows the concentrations of precious and base metals in the three jasperoid samples, as well as concentrations of “Carlin-suite” trace elements (As, Tl, Hg, Sb, and Ba) and trace elements that are typically considered igneous-related (Bi, Li, Ni, and W). Sample SC-002, the hematitic jasperoid, contains low concentrations of Au, Ag, base metals, and trace elements and is essentially barren. By contrast, samples SC-001a and SC-001b contained 0.207 and 0.09 ppm Au and significantly elevated concentrations of As, Tl, Hg, Sb, and Ba. However, these two samples also contained elevated concentrations of base metals and igneous-related trace elements.

**Stable isotope analysis**

A small number ($n = 14$) of surface samples were collected and analyzed for carbon and oxygen isotopes. Samples included both visually altered and unaltered limestone and dolomite wall rock as well as veins hosted by the Eldorado Dolomite, Hamburg Dolomite, and Pogonip Group (Table 1). For this
study, isotopic compositions of samples from a wide range of alteration types across the Eureka district were calculated and compared with compositions calculated by previous studies for fresh and unaltered sedimentary and igneous rock. Rather than determining the extent to which isotopic exchange has occurred (Hastings, 2008), which would require a large and closely-spaced data set, the goal of this investigation was to capture some of the variability in isotopic signatures associated with carbonate replacement deposits, as well as lower-temperature formation of the Carlin-type system at Archimedes).

Figure 15 shows the range of $\delta^{18}$O$_{SMOW}$ compositions for a variety of rocks in the Eureka district, including mid-Cretaceous igneous intrusions, quartz-base metal veins, jasperoid, mineralized limestone and calcite veins at Archimedes, unaltered carbonate rock, and sedimentary chert. $\delta^{18}$O$_{SMOW}$ compositions for mid-Cretaceous igneous rocks range from 7–10‰ (Vikre, 1998); by contrast, visually unaltered Hamburg Dolomite (this study) and sedimentary chert (Barton and Ilchik, 1995, unpublished internal report to Homestake Mining Company) have $\delta^{18}$O$_{SMOW}$ ranging from 12 to 20‰. As is typical of many Carlin-type deposits, mineralized wall rock from the Archimedes deposit exhibits a range of $\delta^{18}$O$_{SMOW}$ from 12 to 20‰ (Hastings, 2008). Material collected from skarn adjacent to the Graveyard Flat intrusion and from silicified rock with high Au grade near the Blanchard fault, which postdates the intrusion, exhibit similar degrees of depletion, further indicating that Carlin-type mineralization is associated with a post-Cretaceous hydrothermal system entirely separate from the magmatic-hydrothermal system that produced the polymetallic carbonate replacement mineralization (Hastings, 2008).

Samples of limestone from the Pogonip Group collected east of Austin Canyon (Table 1; Figure 15) have $\delta^{18}$O$_{SMOW}$ of 18‰, whereas samples from sparry calcite veins in this location have $\delta^{18}$O$_{SMOW}$ of ~8–9‰.

**Table 1. TRACE-ELEMENT CONCENTRATIONS OF SELECTED JASPEROID SAMPLES.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Au (ppm)</th>
<th>Ag (ppm)</th>
<th>As (ppm)</th>
<th>Ti (ppm)</th>
<th>Hg (ppm)</th>
<th>Sb (ppm)</th>
<th>Ba (ppm)</th>
<th>Cu (ppm)</th>
<th>Pb (ppm)</th>
<th>Zn (ppm)</th>
<th>Bi (ppm)</th>
<th>Li (ppm)</th>
<th>Ni (ppm)</th>
<th>W (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-001a</td>
<td>0.207</td>
<td>&gt; 100</td>
<td>7320.0</td>
<td>3.05</td>
<td>60.50</td>
<td>61.10</td>
<td>160</td>
<td>79.1</td>
<td>5140</td>
<td>6300</td>
<td>0.08</td>
<td>41.2</td>
<td>17.9</td>
<td>1.7</td>
</tr>
<tr>
<td>SC-001b</td>
<td>0.09</td>
<td>&gt; 100</td>
<td>6550.0</td>
<td>3.00</td>
<td>48.50</td>
<td>59.10</td>
<td>130</td>
<td>68.1</td>
<td>4530</td>
<td>6260</td>
<td>0.07</td>
<td>37.5</td>
<td>15.0</td>
<td>1.2</td>
</tr>
<tr>
<td>SC-002</td>
<td>0.005</td>
<td>0.02</td>
<td>83.3</td>
<td>0.43</td>
<td>0.41</td>
<td>1.09</td>
<td>50</td>
<td>1.4</td>
<td>3</td>
<td>7</td>
<td>0.03</td>
<td>5.4</td>
<td>2.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Figure 15. Variation in oxygen isotope values for altered and unaltered igneous and sedimentary rocks in the Eureka district. From right to left, symbols in black represent values for: visually unaltered Hamburg Dolomite and sedimentary chert; Pogonip Group wall rock and calcite veins from the Archimedes deposit; Pogonip Group (Goodwin Formation) wall rock and calcite veins from outside the mine site, west of Austin Ridge; jasperoid; quartz-base metal veins; and Cretaceous intrusive rocks. Symbols in red represent calculated isotopic compositions of a fluid in equilibrium with K9 at 600°C and 300°C; based on empirical quartz–H2O fractionation curve from Taylor (1979).**

**Notes:**

*Vikre, 1998;
**Barton and Ilchik, 1995, unpublished internal report to Homestake Mining Company;

**INTERPRETATIONS**

**Stratigraphic separation on the Jackson-Lawton-Bowman normal fault system**

Stratigraphic separation diagrams plot the stratigraphic unit in both the footwall and hanging wall of a fault against the distance along the trace of the fault (Woodward et al., 1989). Although stratigraphic separation diagrams are most commonly employed in fold-and-thrust belts to interpret the behavior and geometry of thrust faults (e.g., DeCelles and Coogan, 2006), they can also be used in extensional settings to illustrate the displacement geometry associated with normal faults (e.g., Chapman et al., 1978). Stratigraphic separation diagrams are particularly useful tools for identifying and illustrating individual fault segments in complex normal fault systems, which commonly have multiple displacement maxima and minima (Schlische, 1995), and in settings in which compressional structures have been overprinted by later extension, such as the Eureka district.

Normal faults omit stratigraphic section and slide younger rocks down against older rocks. Therefore, on a stratigraphic separation diagram the curve representing the hanging wall of the fault should be located above the curve representing the footwall of the fault if stratigraphic separation is “normal.” A reversal of this pattern, known as a separation anomaly (i.e., footwall curve above hanging wall curve) suggests that either
the fault has changed from a normal fault to a thrust fault or that
the fault cuts an older structure (Groshong, 2006). Displace-
ment along normal faults is greatest near the center of the fault
and decreases to zero at the tips (e.g., Walsh and Watterson,
1991), resulting in a synclinal geometry in the hanging wall
and a stratigraphic separation pattern resembling a smile. Nor-
mal faults commonly tilt as they move, and the mid-fault re-
gions of faults, which are the areas of greatest slip, tend to have
shallower dips than near the ends where slip diminishes to zero
(Schlische, 1995).

Figure 16a shows stratigraphic separation from south to
north along the Jackson fault system in the southern half of
the Eureka district, where the fault zone is mapped as a single
strand. From the measured starting point at the southern edge
of the district, stratigraphic separation gradually decreases
from 500 m to tens of meters at roughly 4 km from the starting
point, indicating that the segment is closing to the north toward a fault
tip. The large amount of stratigraphic separation at the measured
starting point and the absence of a corresponding southern tip
suggest that the Jackson fault system extends southward out of
the Eureka district. There is a short gap in the mapped trace
of the Jackson fault 4 km north of the starting point, further
indicating a zone of low displacement that marks the boundary
between two faults where the rocks on the hanging wall side of
the fault are older than rocks on the footwall side. Rather than
indicating a sudden switch in the slip direction of the fault (i.e.,
from down-to-the-east to down-to-the-west displacement), this
separation is interpreted to mark the point at which the Jackson
fault cuts the older Eureka culmination.

Figure 16b shows stratigraphic separation along the trace
of the Jackson branch, from the FAD shaft to the northern
boundary of the district. From 0 to 0.5 km north of the FAD
shaft, separation is ~200 m. From 0.5 to 1.25 km north of the
FAD shaft there is an abrupt, short separation anomaly where
the Jackson branch is mapped as having rocks of the Bull-
whacker member of the Cambrian Windfall Formation in its
hanging wall and Lower Ordovician Goodwin member (Og1)
in its footwall, suggesting that either a) there is a small thrust
“slice” of Cambrian Bullwhacker in this location, or that b) the
unit in the hanging wall of the Jackson branch has been mis-
mapped. This separation anomaly also marks the point at which
the Holly fault splits from the Jackson branch, with the Jackson
branch continuing on to the northeast and the Holly fault splay-
ing out to the northwest. North of this junction, separation is
normal to the northermost extent of the fault trace.

Significance of the Hoosac fault

The Hoosac fault has been interpreted to be both a contrac-
tional feature (e.g., Nolan, 1962; Taylor et al., 1993; Lisenbee
et al., 1995) and an extensional feature (e.g., Hague, 1883; No-
lan et al., 1974; Long et al., 2014). The Hoosac fault is located
outside the map area but on the eastern side of the district-scale
cross section (Figure 6).

Nolan’s (1962) map of the Eureka district shows the type
exposure of the Hoosac fault on Hoosac Mountain as consisting
of Ordovician Eureka Quartzite to the east, in the footwall, and
Cretaceous Newark Canyon Formation to the west, in the hang-
ing wall. As mapped, this juxtaposition constitutes a younger-
on-older relationship or stratigraphic omission that is sugges-
tive of a normal fault. Nolan (1962, p. 25), however, considered
the overall sinuosity of the fault’s trace to be more compatible
with a “thrust fault of moderate to low dip,” seems to have
deemed Hague’s (1883) interpretation of the fault as having
more than 3.5 km of normal offset unlikely, and asserted that
“a thrust fault would be structurally in accord with the nature of
faulting throughout the district.” By contrast, Long et al. (2014)
describe a series of stratigraphic omissions on Hoosac Moun-
tain and suggest that earlier thrust interpretations be abandoned
in favor of a normal fault system interpretation.

Reconnaissance investigations support the original inter-
pretation of Hague (1883) and the more recent interpretations
by Long et al. (2014), rather than the thrust interpretation, main-
ly because the original juxtaposition of units as described by
Nolan (1962) is indicative of stratigraphic omission and, there-
fore, a normal fault. There is simply not enough “room” for
the entire stratigraphic section to be present without significant
stratigraphic omission. Between 80 and 250 m of limestone of the
Pogonip Group, dipping 43–48°E, is present on the western
flank of Hoosac Mountain above the Rustler pit. Although an
unfaulted section of the Pogonip Group has not been measured
anywhere in the Eureka district, Nolan et al. (1956) estimated
that roughly 490 m of limestone of the Pogonip Group is pres-
ent in the “somewhat faulted” section in Goodwin Canyon and
that roughly 600 m are present on the northern side of Windfall
Canyon. Therefore, it appears that a significant portion of the
Pogonip Group has been faulted out on Hoosac Mountain.

The interpretation here that the eastern third of the Eure-
ka district is dominated by extensional features does not pre-
clude the existence of a major thrust fault at depth, as has been
proposed by a number of workers (e.g., Lisenbee et al., 1995;
Lisenbee, 2001; Long et al., 2014).

Major fault blocks in present-day cross section

The district-scale cross section 104000N, which extends
4 km from west to east across northern Eureka district, can be
interpreted in terms of five major fault blocks, although it also
contains several smaller blocks (Figure 6). The five large fault
blocks are described from west to east.

The first block, the Spring Valley block, consists of Devo-
nian Devils Gate Limestone on the floor of Spring Valley in the
hanging wall of the Sharp fault, juxtaposed against moderate to
steeply west-dipping Cambrian Prospect Mountain Quartzite in
the footwall of the fault (Figures 6, 7). This juxtaposition con-
stitutes an omission of at least 2.4 km of stratigraphic section.

The second block, the Mineral Hill syncline block, con-
ains a syncline with an overturned western limb consisting
Figure 16. Stratigraphic separation diagrams. Crosshatch pattern represents anomalous stratigraphic separation (i.e., the line representing the stratigraphic level of the hanging wall crosses the line representing the stratigraphic level of the footwall), which indicates that the fault either has cut an older structure or switched from down-to-the-east to down-to-the-west offset. (a) Stratigraphic separation diagram for the main branch of the Jackson fault from the southern boundary of the Eureka district north to the vicinity of the Eureka tunnel, at which point the fault splays into the Jackson and Lawton branches. (b) Stratigraphic separation diagram for the Jackson/Holly branch from north of the FAD shaft to north of the Archimedes pit.
of Cambrian carbonate rocks (Figures 6, 7). The syncline is flanked to the west by Cambrian Prospect Mountain Quartzite; the contact of the west-dipping quartzite with gently east-dipping Eldorado Dolomite in the nose of the syncline is an older-on-younger relationship, suggesting the presence of a contractional structure. Although the contact between the well indurated Prospect Mountain Quartzite and Eldorado Dolomite seems an unlikely slip surface, the Prospect Mountain Quartzite on the western flank of Prospect Ridge contains thin-bedded siltstone and shale layers, which are well exposed in Cave Canyon and which could have accommodated a reverse fault. The eastern boundary of this block is marked by the Lawton branch, which juxtaposes moderately west-dipping Hamburg Dolomite in its footwall against more steeply west-dipping Secret Canyon Shale and Geddes Limestone in its hanging wall.

The third block, the Lawton branch block, is a small block bounded on the west by the Lawton branch and on the east by the Prospect Mountain Quartzite (Figures 6, 7). In this block, the stratigraphic order is reversed relative to the rocks in the Mineral Hill syncline block; that is, the rocks young from east to west rather than from west to east. Although the rocks in the Lawton branch block might appear to be simply the eastern limb of the Mineral Hill syncline, the fact that they are (1) in fault contact with the syncline, omitting stratigraphic section, and (2) dipping too steeply to the west to allow the full thickness of the Hamburg Dolomite to be present in the core of the syncline, suggest that this block has been down-dropped by a normal fault. Because the block is stratigraphically inverted relative to the western limb of the Mineral Hill syncline, it cannot be sourced from that limb without significant rotation. Instead, a more likely interpretation is that it was faulted from the western limb of the adjacent anticline of an anticline-syncline pair.

The fourth block, the Buckeye fault block, exposes gently east-dipping Prospect Mountain Quartzite (Figures 6, 7). To the west, the quartzite is in fault contact with the west-dipping Eldorado Dolomite in the Lawton branch block. To the east, the quartzite is in fault contact with the moderately east-dipping Clarks Spring member of the Secret Canyon Shale. The contact between these two units historically has been interpreted as the lowermost thrust fault of a duplex (Figure 6). As noted above, the map pattern shows that this fault cuts down section, making the thrust interpretation unlikely (Figure 16). This study, therefore, reinterprets the fault as a normal fault that juxtaposes Prospect Mountain Quartzite from the core of a fault-propagation fold against the Eldorado Dolomite to the west, as explained further below. Although only the Prospect Mountain Quartzite is exposed at the surface (Figure 6), drill hole HRH-141 penetrated dramatically thinned Prospect Mountain Quartzite (6 m), Eldorado Dolomite (3 m), and Geddes Limestone (15 m) in fault contact at depth. These fault slices are interpreted as splays of the Jackson branch.

(5) The fifth block, the Jackson branch block, is located east of the Jackson branch and consists of a relatively unbroken panel of moderately east-dipping beds, from the Clarks Spring member of the Cambrian Secret Canyon Shale to the Permian Carbon Ridge Formation. Anomalies in stratigraphic thicknesses (i.e., in the thickness of the Hamburg Dolomite) suggest that small, previously unrecognized normal faults have omitted stratigraphic thickness in this panel.

**Crosscutting relationships, ages of events, and assessment of structural controls for mineralization**

This section summarizes the current understanding of the sequence of geologic events in the district based on crosscutting relationships and other information, which will be a basis for a subsequent structural reconstruction, as well as the evidence that certain faults did or did not serve as conduits for hypogene mineralization in either the mid-Cretaceous or late Eocene (?) events.

The host rocks in the district were deposited in the Cambrian and Ordovician. It is possible that some folds or thrust faults are of mid-Paleozoic age, but the age of contraction and growth of the Eureka culmination was concurrent with deposition of the synorogenic Early Cretaceous Newark Canyon Formation at ~116 Ma (Aptian) (Druschke et al., 2011; Long et al., 2014). The Ruby Hill stock was emplaced and associated alteration and carbonate-hosted base metal mineralization were formed at ~106 Ma (Mortensen et al., 2000), which is Albian, i.e., late Early Cretaceous, or ~10 m.y. after contractional deformation.

Workers in the northern Eureka district have entertained hypotheses that many faults possibly were conduits for fluids that produced base-metal mineralization, yet it is now established that many of the faults clearly offset the Ruby Hill stock and base-metal mineralization, as is also supported by data from ground magnetics and drilling (e.g., Figures 2 and 3 of Vikre, 1998). The northwest-striking, down-to-the-northeast Ruby Hill normal fault, along with the Martin and perhaps the Office faults, is one of the earliest normal faults to cut and offset the Ruby Hill stock and mid-Cretaceous carbonate-hosted base metal mineralization. The Jackson branch cuts and offsets the Ruby Hill fault; the Lawton branch cuts marble at Mineral Hill (Figure 9) that is related to the intrusion of the Ruby Hill stock (this study). Because the northwest-striking Ruby Hill normal fault cuts and offsets mid-Cretaceous mineralization and is in turn cut and offset by the Jackson branch, the Jackson fault cannot have acted as a conduit for Cretaceous magmatic-hydrothermal fluids. The west-northwest striking, down-to-the-north Blanchard and Molly faults, which control Carlin-type gold mineralization in the Archimedes pit (e.g., Dilles et al., 1996), may be members of the same fault set as the Ruby Hill fault and thus could be the same age. The age of Carlin-type ores in the district may be late Eocene but remains somewhat uncertain; although good radiometric dates on volcanic rocks that exist, their relationship to the age of hypogene gold deposition in some cases requires further investigation (C.D. Henry, written commun., 2014; Barton et al., 2015).

Mapped alteration patterns (jasperoid, marble, bleaching,
and sanding of carbonates), which spatial relationships and isotopic studies suggest are related to the Cretaceous magmatic-hydrothermal system, nonetheless show no relationship to the Jackson fault (this study). This is consistent with the fact that faults of the down-to-the-east Jackson fault system cut and offset the down-to-the-north faults that control Carlin-type gold mineralization. The Jackson fault system is interpreted also as post-ore in age relative to Carlin-type gold mineralization because it cuts and offsets the down-to-the-north faults. Structural reconstructions (see below) suggest that the east-dipping Jackson normal fault system predates movement on the late Cenozoic, range-bounding, west-dipping Sharp fault, as the Sharp fault cannot predate the Jackson fault because there would be no logical source for the west-dipping, stratigraphically inverted rocks in the hanging wall of the Lawton branch (Figure 6). Thus the Jackson fault system is probably mid-Cenozoic in age, postdating the Ruby Hill, Blanchard, and Molly faults and predating the late Cenozoic Sharp fault.

District-scale structural reconstruction

The cross section of Figure 6 is used to make a stepwise structural reconstruction of normal faulting in the northern Eureka district (Figure 17). To achieve a rigorous reconstruction, the slip directions of all faults should be in the plane of the cross section (e.g., Dahlstrom, 1969). This is unlikely to be strictly the case in this example, with numerous fault sets involved, although most of the faults strike nearly perpendicular to the cross section (Figures 7, 8, 10, 12). Thus, we use the cross section only to make a first-pass diagrammatic reconstruction.

A significant challenge common to many areas where complex extensional deformation has been superimposed on contractional deformation (e.g., Pape et al., 2015) is that the geometry following contraction is not tightly constrained. Some of the considerations are: How many generations of normal faults are there, and how much tilting was associated with each generation of normal faults? Are the folds all formed during contraction? Did contractional folds form by fault-propagation folding, fault-bend folding, or some other mechanism? How many reverse faults are present?

Although it is clear that the subsequent extensional structures dismembered the contractional structures that formed the Eureka culmination, it is less clear how much tilting was associated with each generation of normal faults and how much net tilting occurred during extension. Constraints on the amount of tilting associated with each generation of faults is necessary to restore movement on faults and to reconstruct the original orientations of the faults, but abundant pre-, syn-, and post-kinematic strata are needed to monitor tilting (e.g., Seedorff et al., this volume, b). Nonetheless, the net tilting resulting from movement on all faults in the Eureka would not necessarily be significant because faults of various polarities, including both down-to-the-east and down-to-the-west normal faults are present, so the tilting related to individual faults sets may nearly be canceled out by back rotation by other sets. Unfortunately, there are few Tertiary rocks present in the district to provide constraints on tilting and its association with certain sets of faults. The Target Hill dome (~35.9 Ma, C.D. Henry, written commun., 2014) is a few km northeast of the map area, but normal faulting and associated tilting may have preceded and postdated its emplacement. It appears relatively upright and intact, and associated pyroclastic rocks near the town of Eureka dip only gently (12–20°) to the northeast, and dips that shallow might be primary dips. Hence, the net tilting is uncertain; it might be gently northeast; it might be zero, or neither. In the absence of evidence to the contrary, we assume it is negligible. We also assume that all folding is related to contractional deformation, which is a defensible first approximation, although in detail it is likely to be incorrect because some flexural bending associated with normal faulting is likely (e.g., Seedorff et al., this volume, b).

If the net extensional tilting is negligible and no folding occurred during extension, then the attitudes of Paleozoic rocks can be assumed approximately to represent their pre-extensional attitudes. Beds that are overturned (Figure 6), which are widespread on the western side of the district (e.g., Nolan, 1962), thus were not overturned by extension-related tilting, as is the case in the Egan Range (Seedorff and Maher, 2002), but were overturned during earlier deformation. Syncline-anticline pairs with an overturned syncline in the footwall of the reverse fault are typical of fault-propagation folding but not fault-bend folding (e.g., Shaw et al., 2005), so a reverse fault with a fault-propagation fold should be the targeted structural architecture for the restoration to achieve. For simplicity—which is warranted given the paucity of constraints—we assume the presence of only one reverse fault, although having more than one reverse fault or a master reverse fault with several splays would not be unreasonable in a contractional setting (e.g., Schmidt and Perry, 1988).

We then attempt to restore faults in a stepwise manner, beginning with the youngest and ending with the oldest (Figure 17). Although we assume no net tilting, there may have been considerable tilting associated with movement of any particular generation of faults, so the attitudes of faults at various stages in the reconstruction (Figure 17) are not necessarily representative of their initial attitudes.

Four generations of faults (one reverse and three later sets of normal faults) crop out in the cross section. To generate a reasonable reconstruction following the above assumptions without ignoring the lithologies and bedding attitudes in even the small fault fragments, it is necessary to include a fault that does not crop out at the surface in the line of section, which is not unusual in reconstruction involving faults with significant offsets. This fault would belong to a set of faults that crops out elsewhere in the area, from an early generation of down-to-the-west faults (Figure 6), such as the Dugout fault. The only fault set(s) that is significant in the northern Eureka district that is not represented in the cross section and reconstruction (Figures 6
Figure 17. Diagrammatic stepwise restoration of district-scale cross section 104000N through the northern Eureka district, looking north. The figure shows the present cross section from Figure 6 and stepwise restoration of four, color-coded sets of normal faults, with locations of key faults and positions of displaced present-day geologic surface labeled. Fifth stage shows Champion reverse fault and an associated fault-propagation fold. Note that units beneath Cambrian Prospect Mountain Quartzite and above Mississippian Chainman Shale, including any synorogenic deposits, are omitted.
and 17) is the northeast-dipping set that includes the Ruby fault and perhaps the Blanchard. Figure 17 shows the stepwise restoration of faults on cross section 104000, including where the present surface is located during each step of the restoration. The younger west-dipping normal faults (e.g., Sharp fault) appear to be the youngest fault set, and they are restored first. The Sharp fault has an offset of ~1.6 km in the plane of the cross section. Then the younger set of east-dipping faults is restored, and the Hoosac fault has an offset of ~1.0 km in the plane of the cross section. Then an older, more gently dipping set of east-dipping faults is restored (e.g., Jackson, Lawton, and Buckeye faults). Indeed, movement on the faults of the Jackson normal fault system must predate slip on the range-bounding Sharp fault; otherwise there would be no logical source for the west-dipping, stratigraphically inverted rocks in the hanging wall of the Lawton branch. The panel of east-dipping rocks in the hanging wall of the Jackson branch is restored to its pre-extension geometry by sliding rocks in the hanging walls of the Lawton, Jackson, and Buckeye faults a total of ~3 km up dip (i.e., to the nose of the Eureka culmination, from which they were sourced).

This results in the pre-extension structural architecture of the district as a fault-propagation fold with an apparent offset in cross section 104,000N of ~2.8 km formed by growth of the Champion fault. Figure 18 shows an enlargement of the final panel of Figure 17, with a possible view of the pre-erosional, pre-extensional structural architecture of the district. The total extension across this section is somewhat >100%.

Reconstructions in the Eureka district might be improved in the future by adopting a three-dimensional approach to reconstruction (e.g., Seedorff et al., this volume, b) and incorporating drill hole results in the district.

Controls on Carlin-type gold mineralization in the northern Eureka district and implications for mineral exploration

With the exception of carbonate bleaching, alteration in the northern Eureka district shows no spatial association with the Jackson fault zone; most of the mappable alteration in this part of the district appears to be spatially related to the mid-Cretaceous (~106 Ma) Mineral Hill stock (Figures 9, 11). Mapping and reconnaissance isotopic analyses suggest that alteration in the limestones of Ordovician Pogonip Group just east of Austin Canyon (an area that might be considered one of the most prospective for Carlin-type mineralization based on lithology, abundant silicification, geochemical anomalies in soils, structural ground preparation, and dearth of drilling) is most likely related to the intrusion of the stock. Prominent hematitic jasperoid outcrops in this area closely resemble jasperoids on the flank of Mineral Hill. Calcite veins in this area are sparry and have light δ18O values relative to the host rock (Table 2; Figure 15) that closely resemble the compositions of mid-Cretaceous intrusive rocks in the district. These depleted values, the general proximity of the samples to the Mineral Hill stock, and the sparry (i.e., high-temperature) texture of the veins suggest that the veins in this area also are the product of the Cretaceous magmatic-hydrothermal system.

As Nolan (1962) noted, the Jackson-Lawton-Bowman normal fault zone does spatially coincide with the belt of most intense carbonate replacement mineralization in the district. The exact timing of movement on the Jackson fault remains poorly constrained. However, the fact that the Ruby Hill fault cuts and offsets mid-Cretaceous mineralization and is in turn cut and offset by the Jackson branch effectively precludes the possibility that the Jackson fault acted as a conduit for Cretaceous magmatic-hydrothermal fluids. The spatial relationship between Cretaceous mineralization and the fault system is, therefore, most likely fortuitous and a function of exposure.

Carlin-type mineralization at Archimedes is structurally controlled, but it is focused along the west-northwest striking, down-to-the-north Blanchard and Molly faults. The Blanchard and Molly faults have significantly smaller offsets (~100 m in both cases) than any branches of the Jackson fault system. The prominent north-south alignment of Carlin-type mineralization in the Eureka district, rather than being related to the Jackson fault zone, is an effect of the strike of the stratigraphic contact between the Hamburg Dolomite and Dunderberg Shale, which is host to gold mineralization at the Paroni, Windfall, and Rustler pits. Whole-rock geochemical analysis of jasperoid samples from the Hamburg-Dunderberg contact in the northern part of the district show that it also localized gold-bearing fluids there, and in concentrations that one might expect from a Carlin-type system (0.09–0.209 ppm). That samples from this contact, which hosts gold-only mineralization at the Paroni, Windfall, and Rustler mines, also contain elevated concentrations of base metals, Li, Ni, Be, and W in the northern Eureka district suggests that Carlin-type fluids may have traveled along this contact, overprinting the Cretaceous base-metal mineralization where it was present (i.e., largely in the northern part of the district, proximal to the Mineral Hill stock) but forming monogenetic Carlin-type deposits in the southern Eureka district, spatially removed from the effects of the mid-Cretaceous system.

Nolan (1962) noted that the low-grade disseminated gold deposits at the Windfall mine are “so distinctive that one might suspect a different source (p. 30)” and also observed that all of the historically mined deposits in the district, which varied in tenor from mine to mine, tended to be relatively rich in gold and arsenic. Titley (1993) compiled Cu, Pb, Zn, Ag, and Au grades for fifty-two carbonate-hosted massive sulfide deposits in the United States and Mexico. Although metal content varies from district to district, gold grades in the carbonate replacement deposits in the Eureka district are conspicuously high (28.28 g/t) relative to other locales. In the 42 districts whose ores contained measurable amounts of gold, the mean gold grade was 3.16 g/t. It, therefore, is plausible that an Eocene (?) Carlin-type overprint on Cretaceous base-metal mineralization may have
Jackson normal fault system, Eureka district

Figure 18. Diagrammatic reconstruction of pre-extensional geometry of northern Eureka district. Enlargement of fifth panel of previous figure, after formation of fault-propagation fold associated with slip on Champion reverse fault. Other faults are normal faults that will form subsequently, shown in the future positions in which they will appear. Units beneath Cambrian Prospect Mountain Quartzite and above Mississippian Chainman Shale, including any synorogenic deposits, are not shown. Pluton at depth intersected by drilling (see Figure 6) and indicated by aeromagnetic data (Vikre, 1998).
enriched the tenor of gold mined from carbonate replacement deposits in the northern Eureka district.

**DISCUSSION**

**The nature of Early Cretaceous contractional deformation**

The Eureka district has been affected by multiple periods of deformation, including a major contractional event associated with the central Nevada thrust belt (e.g., Nolan, 1962; Long et al., 2014) and subsequently multiple sets of normal faults. As noted by Pape et al. (2015), such areas generally require an iterative approach to producing a viable structural restoration, wherein the pre-extensional model is progressively modified to produce a restored extensional structural geometry that satisfies all of the available geologic constraints on the nature of all deformational events. The iterative approach, however, results in a degree of internal circularity within the retrodeformable cross section because the extensional structure and the pre-extensional structural interpretations are not mutually independent, i.e., uncertainties regarding the structure of both the extended and restored states of the cross sections increase the number of potentially valid retrodeformable cross sectional models. The uncertainties are magnified if considerable uncertainties also exist in the field regarding the crosscutting relationships between various structures, as is not uncommon in areas of considerable complexity and imperfect exposure.

Determining the amount and direction of slip in the normal faults is determined by restoring the hanging-wall blocks relative to the footwall blocks in the directions opposite to their slip direction, pinning geologic markers in the hanging wall to offset equivalents of the same markers in the footwall. This process, however, only backs out the movement on the normal faults. Because many normal faults rotate or tilt as they move (e.g., Jackson, 1987), in general this process does not return the fault surface to its orientation relative to a paleohorizontal reference frame prior to the onset of movement for each set of faults, and additional geologic constraints typically are required to determine the original dip of the fault (Seedorff et al., this volume, b). Ideally, one has a series of dated geologic units (e.g., volcanic or syntectonic sedimentary strata) that were deposited throughout the various deformation events, with bed-determined angles available for each so that the orientations of the faults relative to paleohorizontal can be determined as a function of time. The more limited the available geologic constraints, however, the more the resulting interpretation is model-driven, yet controversies remain, for example, regarding the applicability of various models of continental extension (e.g., Wong and Gans, 2008; Wernicke, 2009).

The challenge in central Nevada in general and in the Eureka district in particular is that there are few such constraints on paleohorizontal as a function of time; hence, explicit or implicit assumptions critically affect the resulting interpretation. Such a limitation is acknowledged for the structural interpretation presented here, particularly as it affects the geometry of the contractional structure. Determination of whether fault-bend folds (e.g., Bartley and Gleason, 1990; Long et al., 2014) or fault-propagation folds (this study) characterize the central Nevada thrust belt—or both in different places—probably will depend importantly on finding further constraints on paleohorizontal as a function of time.

**Relative ages of magmatic-hydrothermal replacement ores and contractional deformation**

Since the advent of the theory of plate tectonics it has been
clear that many magmatic-hydrothermal systems—especially porphyry copper deposits—form at convergent plate margins (e.g., Sillitoe, 1972, 2010; Seedorff et al., 2005), yet the timing of local contractional deformation relative to the formation of magmatic-hydrothermal systems has relatively few firm data points (e.g., Potrerillos, Chile: Olson, 1989; Marsh et al., 1997) anywhere in the world. Additional information on the timing of deformation and formation of magmatic-hydrothermal systems would make it possible to assess exploration models calling on formation in areas removed from active contractional deformation, such as in transtensional sites along arc-parallel strike-slip faults (Tosdal and Richards, 2001; see also Richards et al., 2001; Sapiie and Cloos, 2004), versus models inferring ore formation during contraction (Sillitoe, 1998), especially in relays or contractional accommodation zones (Skármeta et al., 2003). Is the relative timing of deformation and magmatism necessarily even that important to whether or not ore formation will occur or the degree to which metals may be concentrated?

The Eureka district is one of several broadly contemporaneous magmatic-hydrothermal systems, including those in the Robinson and White Pine districts, that formed in a back-arc setting from ~98 and 111 Ma at a latitude of ~39°15’N in east-central Nevada (Seedorff et al., this volume, a). The mid-Cretaceous base metal replacement ores and related skarns and greisen veins of the Eureka district (Nolan and Hunt, 1968; Vikre, 1998), which constitute a Mo-Cu type of magmatic-hydrothermal system in the classification of Seedorff et al. (2005), contribute to the diversity of magmatism and associated mineralization in the Mesozoic Cordilleran arc (e.g., Barton, 1990, 1996). The integration of recent geochronological and structural studies (Mortensen et al., 2000; Long et al., 2014) indicates that this magmatic-hydrothermal event occurred ~10 m.y. after Early Cretaceous contractional deformation in the district, thus providing another firm data point in dating the difference in ages of contractional deformation and magmatic-hydrothermal ore formation.

Syn-ore faults in Carlin-type deposits and their impact on gold grade

Although Carlin-type deposits, are known for commonly forming regional-scale “trends” (e.g., Hofstra and Cline, 2000), the trends do not necessarily parallel major faults, and the faults that control ore commonly are small-offset normal faults that strike at high angles to the trend (Seedorff, 1991; see also comprehensive compilation, Tables A1 and A2, Cline et al., 2005). The prominent north-south alignment of Carlin-type mineralization in the Eureka district, rather than being related to the Jackson fault zone, instead is an effect of the strike of the stratigraphic contact between the Hamburg Dolomite and Dunderberg Shale, which is host to gold mineralization at the Paroni, Windfall, and Rustler pits (Barton et al., 2015). In the northern part of the Eureka district, Carlin-type gold mineralization at Archimedes is structurally controlled, focused along the west-northwest striking, down-to-the-north faults such as the Blanchard fault (Dilles et al., 1996), and similar controls exist at deposits elsewhere in the district (e.g., Nolan, 1962). Faults such as the Blanchard, however, have significantly smaller offset (~100 m) than any branches of the later Jackson fault system (this study). As is known from other types of structurally controlled ore deposits and geothermal systems (e.g., Faulds et al., 2011), small-offset faults, irrespective of age, may be more effective at circulating mineralizing fluids through the surrounding rock due to their relatively high pore pressures. In contrast, large-offset faults can act as “drains.”

The complexities of the geology of the Eureka district highlight the challenge of identifying structural controls on Carlin-type mineralization, particularly prior to or beyond the extent of mining-related exposures where the exposure may be limited and where there may be partial spatial overlap between Carlin-type and other mineralizing systems. The challenge is made more difficult when the faults that have the most control on gold grade have relatively small offsets, as is commonly the case.

CONCLUSIONS

The northern part of the Eureka district hosts mid-Cretaceous (~106 Ma) base metal replacement ores and related skarns and greisen veins that constitute a Mo-Cu type of magmatic-hydrothermal system, which was subsequently overprinted by Eocene(?) Carlin-type gold mineralization, including the Archimedes deposit. An Eocene(?) Carlin-type overprint on Cretaceous base-metal mineralization may have enriched the tenor of gold mined from the carbonate replacement deposits. The Jackson-Lawton-Bowman normal fault system extends the length of the Eureka district for 21 km, and the Buckeye fault is likely a fourth branch of the system. The fault system dismembers folds of the Eureka culmination. Structural reconstructions suggest that in the northern part of the district the culmination formed by fault-propagation folding, likely in the Early Cretaceous during development of the central Nevada thrust belt.

Unraveling the structural complexities of the Eureka district remains a work in progress, but the series of superimposed structural, intrusive, and hydrothermal events in the district have been interpreted in this study as follows. Contraction and growth of the Eureka culmination occurred concurrent with deposition of the synorogenic Early Cretaceous Newark Canyon Formation at ~116 Ma, with the possibility that some contractional deformation is as old as mid-Paleozoic. Mid-Cretaceous intrusions were emplaced and associated carbonate-hosted ores formed at ~106 Ma, or ~10 m.y. after Early Cretaceous contractional deformation. Mapped alteration patterns, which spatial relationships and isotopic studies suggest are related to the Cretaceous magmatic-hydrothermal system, nonetheless show no relationship to the Jackson fault. Carlin-type mineralization at Archimedes is structurally controlled, but by the older, west-northwest striking, down-to-the-north Blanchard and Molly
faults. The Jackson-Lawton-Bowman normal fault system post-dates and offsets not only the carbonate-hosted ores but also Carlin-type gold mineralization. Structural reconstructions suggest that the east-dipping Jackson normal fault system nonetheless must predate slip on the late Cenozoic, range-bounding, west-dipping Sharp fault; thus the Jackson is a mid-Cenozoic fault system. The Jackson fault system has no genetic relationship to either the mid-Cretaceous or Eocene mineralizing events, yet these series of down-to-the-east normal faults may be responsible for preventing the erosion of and minimizing the weathering of both the mid-Cretaceous base-metal replacement ores and the higher levels of the Eocene (?) Carlin-type gold ores on the eastern side of the northern Eureka district.

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REFERENCES


