Text and references for Nevada Bureau of Mines and Geology Map 155

GEOLOGY OF THE SANTA RENIA FIELDS QUADRANGLE

ELKO AND EUREKA COUNTIES, NEVADA

by

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INTRODUCTION

This study of the Santa Renia Fields Quadrangle (SRF) is part of a comprehensive geologic and geochemical investigation of the northernmost Carlin trend of gold deposits that includes the east-adjoining Beaver Peak Quadrangle (BP) (Theodore and others, 2003a). The SRF lies astride the northernmost known extent of the Carlin trend in the Tuscarora Mountains of northeast Nevada (fig. 1). The trend in its entirety is inferred to have contained economic concentrations of as much as 150 million oz Au prior to the startup of major mining operations in the early 1960s. The northernmost part of the trend underlies a major part of the southeast quadrant of the SRF (Bettles 2002; Moore, 2002), of which the latter includes four gold mines active in 2004 and several other major gold-silver-mineralized occurrences. It also includes the active Rossi barite mine, and numerous additional barite prospects. Prior to initiation of major mining activities, gold resources of various categories in six major deposits in the quadrangle totaled almost 12 million oz Au (table 1). In addition, unexploited occurrences of gold are known to be present in at least one other mineralized area in the quadrangle: Ag-Sb±Au at the Rodeo Creek occurrence, approximately 3 km northwest of the Dee Mine (Theodore and others, 2003b). Gold at the Joker 99 occurrence (Centerra Gold Inc., press release, 2005), approximately 1.5 km north of the REN Mine near the southeast corner of the quadrangle, and other nearby areas currently (2005) is being explored by Centerra Gold. Most gold resources in the quadrangle reside in rocks below the Roberts Mountains thrust (RMT).

The geology of the SRF has complex district-scale stratigraphic and structural relations that result from geologic events that occurred episodically during a protracted period of geologic time. The most-favored rocks for gold mineralization along the Carlin trend—those beneath the RMT—presently plunge to the northwest beneath a complex pile of mostly siliceous Paleozoic rock, Tertiary volcanic rocks, and Tertiary unconsolidated sedimentary deposits. In the quadrangle, the Carlin trend was inferred to be approximately 4 km wide on the basis of stream-sediment concentrations of arsenic and antimony (Theodore and others, 2003b), and the trend is inferred to extend approximately 10 km northwest into the quadrangle. In this paper, we have widened the surface projection of the trend to approximately 4.5 km on the basis of some recently discovered mineralized rock.

Paleozoic rocks in the SRF include a stratigraphic sequence in the upper plate of the RMT that was thrust into the area during the middle Paleozoic Antler orogeny (see also Roberts and others, 1958; Sandberg and others, 1982; Saucier, 1997; Cluer, 1999; Trexler and Giles, 2000). The upper plate of the RMT includes Upper Ordovician Vinini Formation of Merriam and Anderson (1942) (see also, Finney and Perry, 1991; Finney and others, 2000), Silurian and Devonian Elder Sandstone of Gilluly and Gates (1965), and Devonian Slaven Chert of Gilluly and Gates (1965). At the district scale, stratigraphic and structural relations within the upper plate have been discriminated on the basis of (1) numerous fossil localities, (2) prominent units such as the Silurian and Devonian Elder Sandstone (DSe), as

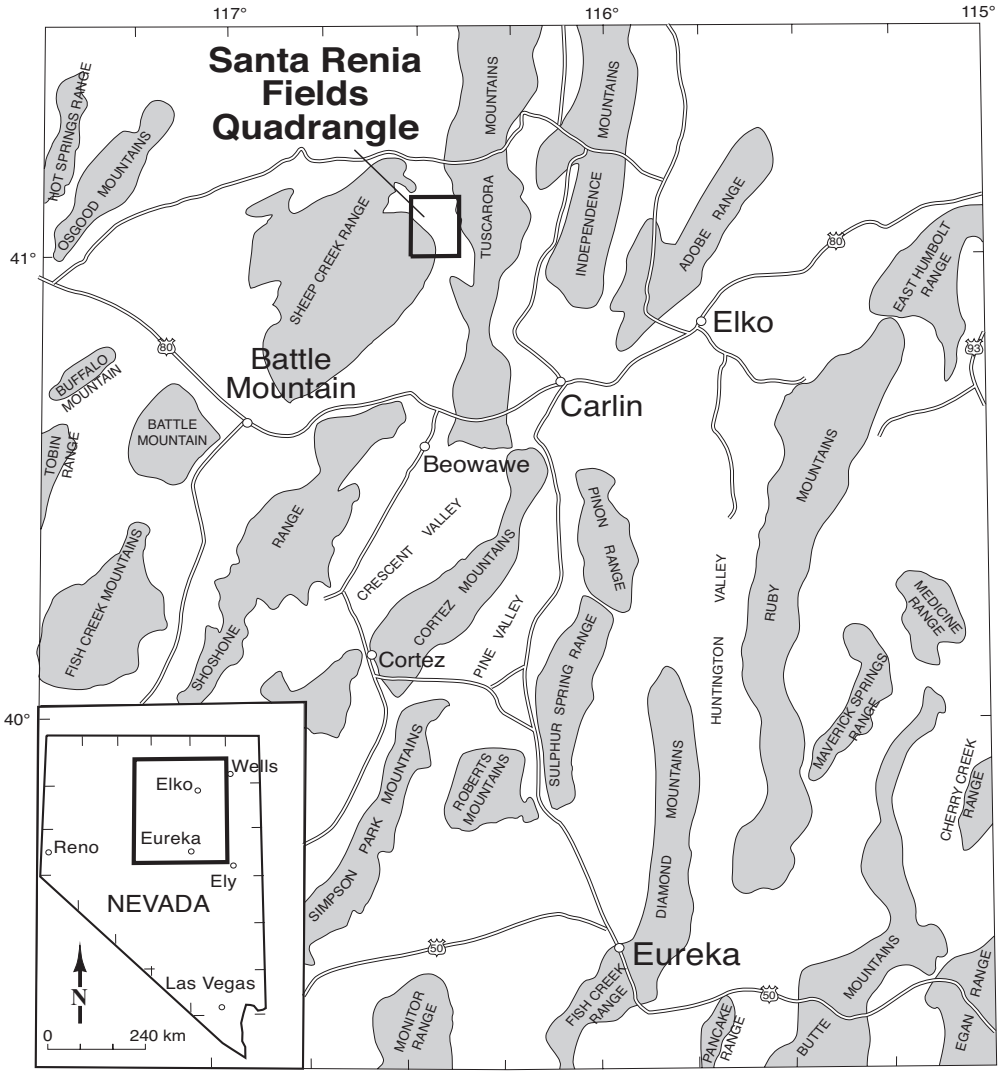

Figure 1. Location map of north-central Nevada.

Table 1. Gold resources of selected deposits near the northern end of the Carlin trend, Nevada[1].

Deposit	Gross tonnage (short tons)	Contained gold (ounces)
Storm[2]	3,100,000	1,100,000
Dee	15,449,000	941,000
Capstone/Tara/ Bootstrap	22,652,000	1,172,000
Meikle	10,011,000	7,141,000
REN[3]	450,000	22,000
REN Centerra[4]	3,456,000	1,307,000

[1]Includes historical production, proven and probable reserves, and inferred mineral inventory. Modified from Albino (1994), Teal and Jackson (1997), Dobak and others (2001).
[2]Includes 49er, End, and Discovery mineralized zones.
[3]Includes only that oxidized near-surface, intrusion-hosted ore mined by Dee Gold Mining Co. during 1989–1990.
[4]Includes an indicated resource of 791,000 oz Au in 2,066,000 short tons, and an inferred 516,000 oz Au in 1,390,000 short tons (Centerra News Release, January 27, 2005).

well as (3) a number of narrow marker horizons of bedded barite (ba) in the Devonian Slaven Chert (units Dsc and Dsm). The Elder Sandstone in the quadrangle is mostly a dolomitic and calcareous very fine sandstone and coarse siltstone. The Slaven Chert includes an extensive chert mélange unit (Dsm) that generally is poorly exposed, and that may include tectonite fabrics that date from the onset of shortening along the RMT.

The rocks in the upper plate of the RMT locally show widespread repetition by subsequent thrusting in the late Paleozoic on the basis of relations with late Paleozoic rocks (Theodore and others, 1998, 2003a) that belong to the overlap assemblage of Roberts (1964). The overlap assemblage comprises a package of late Paleozoic rocks partly eroded from highlands uplifted during the Antler orogeny. Reactivation of the upper plate of the RMT occurred roughly 100 m.y. after onset of shortening along the RMT during the Late Devonian and Early Mississippian. Thrust faults in the SRF that apparently are related to the late Paleozoic shortening event are the Squaw Creek thrust, the Coyote thrust, and the Little Jack thrust, as well as a number of minor thrust faults. In addition, the lower Paleozoic siliceous strata in the quadrangle generally lack widespread altered basaltic rock (greenstone), a fact also noted by Dubé (1987, 1988) in the Lake Mountain area approximately 20 km to the northeast. This absence seems to preclude the presence of widespread syndepositional rifting in these rocks during the lower part of the Paleozoic sequence, although we discuss below evidence for syndepositional movements along some faults during the Devonian. Nonetheless, some minor amounts of basaltic rock are present in lower Paleozoic rock in the SRF. Pyrite replaces feldspar-rich basaltic andesite fragments in thin (<2 m thick) volcaniclastic submarine debris flows that are present in the Ordovician shale and chert unit of the Vinini Formation (Ovsc) approximately 200 m below the surface at the Rodeo Creek mineralized occurrence (Theodore and others, 2003b). Uppermost strata of the Elder Sandstone in the region are as young as early Early Devonian (Noble, 2000) and, at their base, locally contain discontinuous, approximately 10-m-thick sequences of well-bedded knobby black and blue-green chert that probably are correlative with the Cherry Spring chert unit of Noble and others (1997). Rocks in the upper plate of the RMT cover gold-mineralized rocks in the lower plate that commonly are associated with dike swarms and prominent structures.

Chert-pebble conglomerate beds that are less than 50 m thick and that belong to the Pennsylvanian and Permian Strathearn Formation (P$\mathbb{P}$s) of the overlap assemblage are exposed in a number of small structurally dismembered outcrops that extend eastward across the northern quarter of the SRF. This unit has been shown in the east-adjoining Beaver Peak Quadrangle to bracket stratigraphically and temporally the emplacement of a major allochthonous thrust plate of mainly quartzarenite of the Vinini Formation (Ovq) (Theodore and others, 2003a, 2004).

Intrusive rocks of wide-ranging ages and Tertiary unconsolidated deposits and volcanic rocks are present in the SRF. The most prominent intrusive rocks in the quadrangle comprise a swarm of Jurassic biotite lamprophyre dikes (Jbl) that largely strike northwest in the general area of the Dee Mine, and that strike mostly north in the general area of the Capstone-Bootstrap and Tara Mines near the southern boundary of the quadrangle. Much of the western half of the quadrangle is underlain by (1) Miocene volcanic rocks, including a thick pile of phenocrystic quartz-bearing rhyolite flows near the west-central border (Trf), and slightly younger Miocene mostly aphyric rhyolite (Trb) near the southern border; (2) mostly unconsolidated deposits and conspicuous white tuffs assigned to the Miocene Carlin Formation of Regnier (1960); and (3) extensive flat-lying late Tertiary and Quaternary unconsolidated fanglomerate deposits (QTg_2) that include abundant cobbles and boulders of quartzarenite that were apparently derived from topographically high exposures to the east in the Beaver Peak Quadrangle (BP). In addition, other minor intrusive rocks are present in the quadrangle and are described in somewhat more detail below. However, no Eocene felsic intrusive rocks, which are associated with gold resources elsewhere in the Carlin trend (Ressel and others, 2000; Arehart and others, 2003), have been found at the surface in the SRF.

Collaborative geologic mapping by the U.S. Geological Survey (USGS) and private industry in the Tuscarora Mountains forms part of wide-ranging investigations at mining-district scale in northeast Nevada that have been sustained primarily by the Western Region Gold Project of the USGS. The Gold Project, which was recently completed under the leadership of David A. John was, in turn, directly supportive of ongoing regional mineral-assessment tasks and regional geologic and geochemical studies in the Humboldt River Drainage Basin Project of the USGS led by Alan R. Wallace that was completed in 2005 with release of a metallic mineral resource assessment of the Humboldt River Basin (Wallace and others, 2004). The primary objective of all these studies is to advance understanding of the genesis of gold deposits in the region in order that state-of-the-art mineral assessments might be prepared by the USGS upon request by other Federal agencies such as the U.S. Bureau of Land Management.

The SRF is in the Tuscarora Mountains, Nevada, between north latitudes 41°00' and 41°07'30" and west longitudes 116°22'30" and 116°30' (fig. 1). Primary access to the SRF is (1) from the southwest into Antelope Creek, (2) from the Ivanhoe Mining District east into the main drainage of Antelope Creek, and (3) from Boulder Creek, near the south-central part of the quadrangle, where a well-maintained gravel haul road from Dunphy, Nevada, leads to the Tara, Capstone-Bootstrap, and Dee gold mines as well as the Rossi barite mine. Travel along some roads and jeep trails in the southeast part of the area is restricted because of active mining operations.

Previous geologic investigations in the SRF include the regional Elko County geologic map (Coats, 1987), and geologic mapping studies by numerous mining companies and their consultants, including several by S.B. Keith (written commun., 1999; see also Keith, 2003), that cover most of the quadrangle at a scale of 1:6,000. In addition, some areas of the quadrangle are incorporated in theses by Greybeck (1985) and Snyder (1989); detailed biostratigraphic data are included in reports by Evans and Mullens (1976), and Hall (2002), and in a number of unpublished reports by A.G. Harris (written commun., 2000). Armstrong and others (1997, 1998) describe the implications and impacts of Paleozoic sedimentary fabrics and processes in carbonate rocks below the RMT and implications for genesis of Carlin-type gold deposits. Further, Bettles (2002), Berger and others (2001), Theodore and others (1998, 2000a, 2000b, 2003a), and many others, who mostly have focused on the Carlin trend (fig. 2), have summarized many regional aspects of the geology of the area. Baker (1991), Dobak and others (2000, 2001), Jory (2002), Thompson and others (2002), Emsbo and others (2003), Theodore and others (2003b), and Spalding and others (2005a, 2005b, 2005c) describe in detail many of the Au- and Ag-mineralized occurrences in the SRF. The report by Theodore and others (2003b) also illustrates geochemical patterns in several different sample media—primarily stream sediments—along the northernmost Carlin trend. Berger and Theodore (2005) describe the apparent importance of Paleozoic SEDEX accumulations of gold in northeast Nevada, including SEDEX gold present in the Upper Rodeo gold deposit just off the SRF near its southeast corner. In addition, many papers in Tosdal (1998) and John and others (2003) contain data relevant to the geology of the SRF, in particular the location and orientation of deep structures inferred to be present along the Carlin trend (Grauch and others, 2003a; see also, Crafford and Grauch, 2002; Grauch and others, 2003b). Excellent summaries of many regional aspects are included in the various chapters of Wallace and others (2004). Papke (1984) describes the Devonian bedded

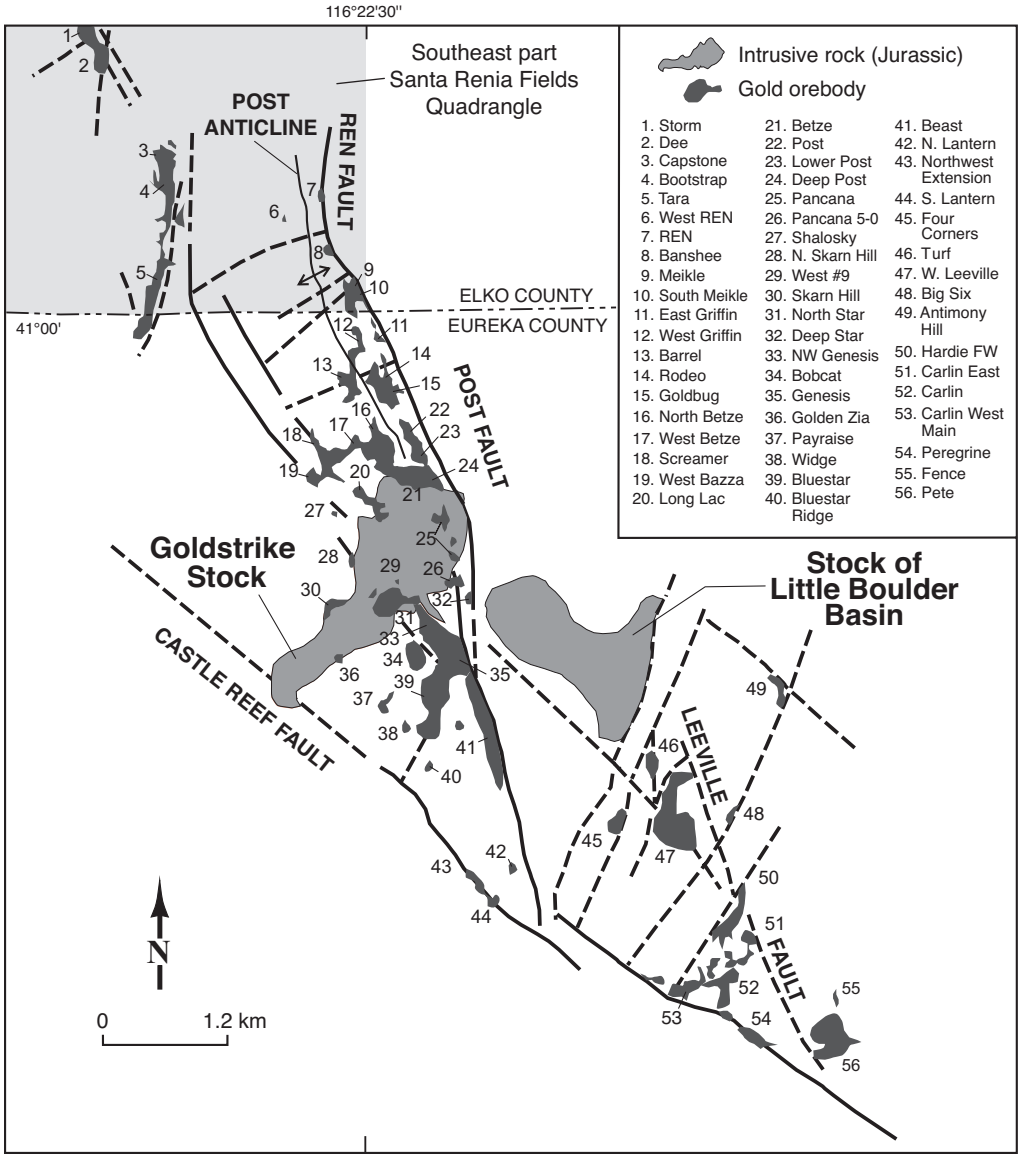

Figure 2. Ore deposits and structural features of the northern Carlin trend, Nevada. Modified from Teal and Jackson (1997).

barite deposits at the Rossi Mine and at the Queen Mine. Fleck and others (1998) discuss the $^{40}Ar/^{39}Ar$ dating of samples of air-fall tuff in the SRF that were obtained from a unit of the Miocene Carlin Formation that includes silt, sand, and mudstone deposits containing abundant tuff (Tcm) (table 2). Although not concerned specifically with the geology of the SRF, the pioneering geologic mapping studies by Evans (1974a, 1974b) in the nearby Rodeo Creek NE and Welches Canyon Quadrangles deserve special mention because of the geologic framework they established along the Carlin trend.

Geologic Framework of the Santa Renia Fields Area, Tuscarora Mountains

The geology of the SRF is discussed in this section beginning with (1) lower Paleozoic rocks below the RMT, followed by a discussion of (2) lower Paleozoic rocks in the upper plate of the RMT, (3) late Paleozoic overlap assemblage rocks that have been deposited unconformably on the upper plate rocks, (4) Jurassic intrusive rocks, (5) miscellaneous intrusive rocks of various ages, (6) Miocene rhyolite flows and intrusive rocks, (7) Miocene rhyolite of Boulder Creek, (8) Miocene Carlin Formation, and, finally, (9) Tertiary and Quaternary unconsolidated deposits.

Lower Plate of the Roberts Mountains Thrust

Two broad structural windows through the RMT expose rocks of the lower plate at the Dee Mine and in the general area of Round Mountain near the south-central border of the SRF. The stratigraphy of lower plate rocks at the Rodeo Creek mineralized occurrence, approximately 3.5 km northwest of Dee, is shown in figure 2. The most widely exposed rocks in the lower plate of the RMT in SRF are at Round Mountain, where they apparently have been uplifted by a number of north-striking normal faults into a >2-km-long, topographically high block. These windows provide a suggestion as to what lithologies might comprise the lower plate of the RMT elsewhere in the quadrangle where only upper-plate rocks are exposed. As indicated on cross sections C–C' and D–D', various formations that make up the lower plate of the RMT have been encountered in numerous drill holes south of the Dee Mine and west of Round Mountain. The stratigraphic succession in the lower

Table 2. Compilation of $^{40}Ar/^{39}Ar$ ages for the Santa Renia Fields, Rodeo Creek NW, and Rodeo Creek NE Quadrangles, Nevada.

Loc. no.	Sample Number	Material Dated	Best Estimate Age (Ma)	MSWD	Comments
			Santa Renia Fields Quadrangle		
1	96TT129	Sanidine	14.43 ± 0.08	1.92	Air-fall tuff, Miocene Carlin Formation
1	96TT130	Sanidine	14.55 ± 0.20	8.62	Air-fall tuff, Miocene Carlin Formation
1	96TT131	Sanidine	14.41 ± 0.04	0.19	Air-fall tuff, Miocene Carlin Formation
2	96TT132	Sanidine	14.48 ± 0.05	0.37	Air-fall tuff, Miocene Carlin Formation
3	96TT133	Sanidine	14.72 ± 0.05	0.24	Air-fall tuff, Miocene Carlin Formation
3	96TT134	Sanidine	14.61 ± 0.10	5.58	Air-fall tuff, Miocene Carlin Formation
4	96TT136	Sanidine	14.93 ± 0.10	3.88	Air-fall tuff, Miocene Carlin Formation
4	96TT137	Sanidine	14.97 ± 0.08	2.59	Air-fall tuff, Miocene Carlin Formation
4	96TT138	Sanidine	14.84 ± 0.04	1.12	Air-fall tuff, Miocene Carlin Formation
5	96TT139	Sanidine	15.01 ± 0.07	6.26	Air-fall tuff, Miocene Carlin Formation
6	96TT151	Sanidine	15.10 ± 0.08	2.80	Air-fall tuff, Miocene Carlin Formation
7	96TT153	Sanidine	15.09 ± 0.11	8.32	Air-fall tuff, Miocene Carlin Formation
8	96TT154	Sanidine	≤15.4 ± 0.3	200.6	Air-fall tuff, Miocene Carlin Formation (Contaminated)
9	96TT157	Plagioclase	<15.9 ± 0.2	0.35	Air-fall tuff, Miocene Carlin Formation (Probable contamination)
10	96TT162	Sanidine	≤14.2 ± 0.1	446.5	Air-fall tuff, Miocene Carlin Formation (Contaminated)
11	979-18B	Sanidine	14.68 ± 0.08	3.10	Thin ash bed in welded tuff, silt, and tuffaceous sandstone unit of Miocene Carlin Formation
12	979-18A	Sanidine	15.01 ± 0.04	0.27	Intrusive rhyolite probably coeval with rhyolite flow unit of rhyolite of Antelope Creek
13	979-18C	Sanidine	14.99 ± 0.05	0.34	Rhyolite flow unit of rhyolite of Antelope Creek; same as Craig rhyolite of Bartlett and others (1991)
14	979-18D	Sanidine	15.16 ± 0.05	0.21	Rhyolite flow unit of rhyolite of Antelope Creek; same as Craig rhyolite of Bartlett and others (1991)
15	979-18E	Sanidine	15.04 ± 0.04	0.20	Rhyolite flow unit of rhyolite of Antelope Creek; same as Craig rhyolite of Bartlett and others (1991)
			Rodeo Creek NW Quadrangle and Rodeo Creek NE Quadrangle		
	97SLRC02	Sanidine	14.92 ± 0.05	0.13	Rhyolite of Boulder Creek; lat. 40.9364N, long. 116.3961E
	97SLRC03	Sanidine	14.91 ± 0.04	0.43	Rhyolite of Boulder Creek; lat. 40.9153N, long. 116.3794E
	97SLRC05	Sanidine	14.97 ± 0.05	0.99	Rhyolite of Boulder Creek; lat. 40.9111N, long. 116.3731E

MSWD, mean square of weighted deviates (McIntyre and others, 1966)

plate of the RMT near Round Mountain includes small exposures of altered massive to thick-bedded gray dolostone that belong to the Ordovician and Silurian Hanson Creek Formation (SOhc); these rocks are the lowermost strata exposed below the RMT.

Two units comprise the Silurian and Devonian Roberts Mountains Formation, which stratigraphically is above the Hanson Creek Formation. The Roberts Mountains Formation is composed of planar laminated, gray carbonaceous silty limestone (DSrm). and the coarse-grained, thick-bedded, informally named Bootstrap limestone of the Roberts Mountains Formation (DSb). At depth at the Meikle Mine, the shelf facies is approximately 640 m thick, and the edge of this shelf—with basinal deposits on the southwest—has been mapped below the surface with a N50°W trend south of Bell Creek near the south edge of the quadrangle (Bettles, 2002). At the Joker 99 gold mineralized area, the contact between the Bootstrap and Popovich contains abundant karsting and brecciation (Spalding and others, 2005c).

At the Rodeo Creek mineralized occurrence, about 300 m of variably altered bioclastic sand to lime mudstone belonging to the Bootstrap limestone have been encountered in a 1,515-m-deep hole (fig. 3) (Theodore and others, 2003b). The Bootstrap limestone was deposited in a largely open platform to supratidal depositional environment (Armstrong and others, 1997, 1998; see also Furley, 2001). The Bootstrap limestone is Late Silurian and Early Devonian (A.G. Harris, written commun., 2001). Spalding and others (2005c) further report a likely Emsian (late Early Devonian) to Givetian (late Middle Devonian) conodont age for Bootstrap strata 18 m below the top of the unit. As a historical sidenote, the Bootstrap limestone near Round Mountain was first examined and described by field parties of the 40th Parallel Surveys (Emmons, 1877).

The Devonian Popovich Formation (Dp) crops out only in two small areas south of Round Mountain, where it is present in depositional contact with underlying Bootstrap limestone (Moore, 2002). However, because the Bootstrap limestone was at times above sea level, its contact with the overlying Popovich Formation commonly includes abundant evidence of dissolution. Dissolution features subsequently channeled groundwater and hydrothermal fluids to form karsts, collapse features, and, eventually, mineralized occurrences (Bettles, 2002). The upper contact of the Popovich Formation with an overlying chert (Drc) belonging to the Devonian Rodeo Creek unit crops out only at the Tara Mine near the south border of the SRF. At this locality the Popovich Formation is approximately 60 m thick. At the Rodeo Creek mineralized occurrence, the top of the Popovich Formation is 933 m below the surface, and mineralized strata of the Popovich make up the basal 106 m of the unit; the base of the Popovich is at a depth of 1,223 m (fig. 3) (Theodore and others, 2003b). Further, lower units of the Popovich Formation, on a district scale, represent a succession of marine lowstand and trangressive systems tracts that pinch out against a high stand system tract that includes the Bootstrap limestone (Furley, 2001). In the area of the Capstone, Bootstrap, and Tara Mines, gold-mineralized rock closely follows the upper contact of the Bootstrap limestone where it is progressively overlapped by successively deeper facies of the Popovich Formation (Jory, 2002). Whereas the Popovich Formation is approximately 210–270 m thick in the general area of the Betze-Post gold deposits (K.H. Bettles, written commun., 2002), six km southeast of SRF, the Popovich Formation is apparently 20–80 m thicker at the Rodeo Creek mineralized occurrence. The Popovich Formation ranges from zero to more than 120 m thick at depth at the Joker 99 mineralized occurrence (Spalding and others, 2005c). The two lower units of the Popovich Formation, as defined by Barrick personnel, are not present at this locality. Some of the apparent thickening and thinning of the Popovich Formation in the SRF may be the result of structural repetition(s), lateral facies variation due to a toe-of-slope depositional environment (Armstrong and others, 1997, 1998), and/or decalcification during mineralization as documented at the Meikle Mine (Emsbo and others, 2003).

Two subunits comprise the Devonian Rodeo Creek unit of Ettner (1989) in the SRF. They are in two fault-bounded blocks near the Dee Mine and in the general area of the Tara Mine. However, the Rodeo Creek unit has been encountered at depth in a broad area around the Dee Mine (see cross section D–D'), as well as at depth at the Joker 99 mineralized occurrence. At the latter locality, conodont ages range from Middle to Late Devonian (Spalding and others, 2005c). A chert subunit of the Rodeo Creek unit (Drc) generally includes black, rhythmically well-bedded, blocky chert that includes siliceous mudstone and chert, as well as minor interbedded sandstone and silty limestone (Moore, 2002). A silty limestone subunit (Drs) crops out only near the south edge of the quadrangle. At the Rodeo Creek mineralized occurrence, the Drc subunit—questionably 600 m thick (Theodore and others, 2003b)—is distinctly thin bedded, is rich in carbon and framboidal pyrite, and includes rare sedimentary slump structures, mud lumps, and millimeter-sized laminae (Armstrong and others, 1998). Although the chert subunit was deposited in a silled, starved anoxic basin (Ettner, 1989), the unit as a whole represents strata transitional between commonly eugeoclinal rocks in the upper plate of the RMT and underlying largely carbonate rocks (Teal and Jackson, 2002). The top of the unit is structurally terminated by the RMT at the Dee Mine.

Upper Plate of the Roberts Mountains Thrust

The best-preserved rock sequences that have relatively undisturbed stratigraphic relations among formations in the upper plate of the RMT are in the BP (Theodore and others, 2003a). In the SRF, the RMT is considered to crop out only at the Dee Mine, where limited outcrops of the shale and chert unit of the Ordovician Vinini Formation (Ovsc) have been structurally superposed onto chert of the Devonian Rodeo Creek unit (Drc) of the lower plate. Unfortunately, in the SRF, many relations among upper plate units are not

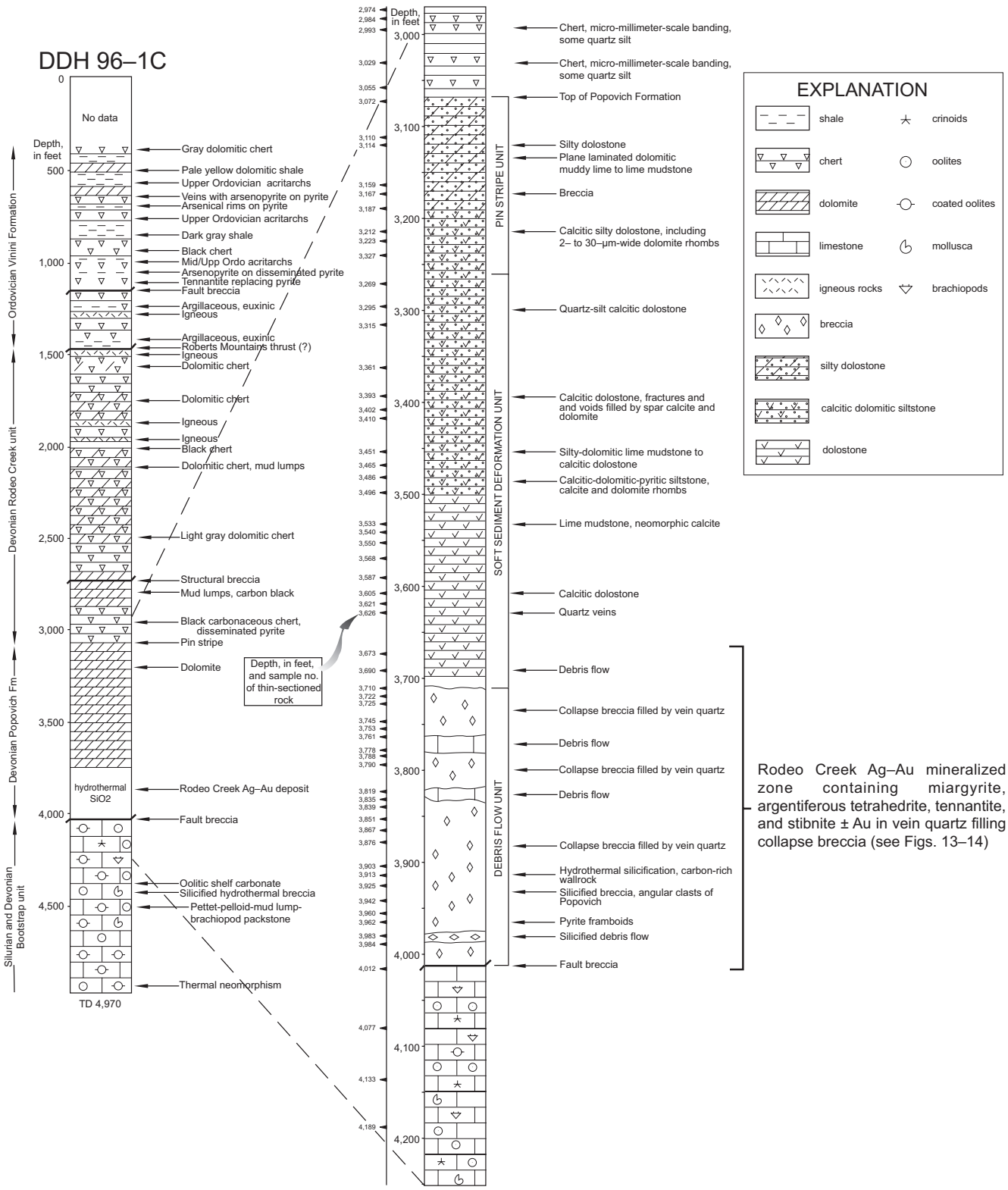

Figure 3. Geology of drill hole 96–1C showing an expanded section through the Devonian Popovich Formation, including depths (in feet) and thin and(or) polished sections examined. Site of drill hole is in area of surface projection of Rodeo Creek mineralized occurrence (loc. 3). Modified from Theodore and others (2003b).

well exposed, and, in fact, are locally quite obscure. This especially pertains to the two Slaven Chert units. A number of thrust surfaces are mapped in the upper plate of the RMT, including the Sink thrust at the base of the Silurian and Devonian Elder Sandstone (DSe). The lowermost allochthon of the RMT includes Ordovician shale and chert (Ovsc), which crops out most extensively near the southeast corner of the quadrangle, and Ordovician, Silurian, and Devonian siliceous rocks undivided (DSOu) that crop out along the east flank of Round Mountain. However, these siliceous rocks along the east flank of Round Mountain may belong to the Rodeo Creek unit. Structurally lower strata of the Vinini Formation in the general area of the REN deposit are overlain by a package of strata of the Vinini along an apparently substantial thrust fault (Spalding and others, 2005c).

The lowermost allochthon of the RMT also includes a well-bedded chert unit (Dsc) of the Devonian Slaven Chert and underlying Silurian and Devonian Elder Sandstone (DSe). The base of the Elder Sandstone is either depositional with underlying chert and shale of the Vinini Formation or as structurally imbricated wedges marked locally by presence of the Sink thrust. Near the Dee Mine, the Elder Sandstone is a well-differentiated interbedded sequence of mudstone, chert, silty dolomitic mudstone, and dolomitic mudstone wherein chert makes up approximately 50 volume-percent of the sequence. This sequence is suspended load dominated. To the north, the Elder Sandstone is mostly silty dolomite, dolomitic siltstone, and fine sandstone, as well as a few mudstone and chert intervals. Bedload sedimentation predominates with broad climbing ripple cross-laminations and plane parallel laminations. These sedimentary features suggest rapid deposition in a significantly shoaled environment subject to moderate currents with an abundant quartz-feldspar, well-sorted, silt and/or fine-sand source. Some sequences of the Elder Sandstone in the Shoshone Range, approximately 100 km to the south-southwest, include sparse thin carbonate beds (Gilluly and Gates, 1965). The age of the Elder Sandstone in the SRF is middle-late Early Silurian.

The presence of rhyolitic volcaniclastic rock locally near the stratigraphic base of the Elder Sandstone near the REN Mine represents some of the oldest examples of felsic magmatism in lower Paleozoic rocks in the allochthon of the RMT. In the Shoshone Range, Gilluly and Gates (1965) also report the presence of shard outlines in K-feldspar-rich shaly siltstone belonging to the Elder Sandstone. Detrital grains of K-feldspar also are abundant in the Elder Sandstone in the SRF. Absence of carbonate minerals from sequences of the Elder Sandstone near the Dee Mine may be due to alteration associated with gold mineralization.

Overlap Assemblage

The mostly siliceous upper plate rocks of the RMT are overlain unconformably—locally in several places with an angular discordance of about 30° in the BP (Theodore and others, 2003a)—by a mostly chert-pebble conglomerate of the Strathearn Formation (P$\mathbb{P}$s), which comprises the overlap assemblage of the Antler orogen in the area. Fossiliferous strata have not been found in this unit in the SRF. However, the strata have been traced to the east into the BP, albeit discontinuously, where well-constrained conodont and fusulinid biostratigraphic determinations have established its age (Berger and others, 2001; Theodore and others, 2003a). These strata are equivalent in age to the lower unit (Cashman and others, 2001) of the Strathearn Formation of Dott (1955) at Carlin Canyon, approximately 10 km east of Carlin, Nevada (see also Trexler and others, 2004). The Strathearn Formation in the BP ranges in age from middle Late Pennsylvanian to middle Early Permian (see also, Berger and others, 2001; Theodore and others, 2000a, 2004). The Strathearn Formation is equivalent in age to the upper parts of the Pennsylvanian and Permian Oquirrh Group in west-central Utah (Roberts and others, 1965), as well as the Pennsylvanian and Permian Antler Peak Limestone of the overlap assemblage at Battle Mountain, Nevada (Roberts, 1964). In addition, the Strathearn Formation also crops out extensively in the Snake Mountains approximately 100 km to the northeast, where its undeformed basal strata rest unconformably on deformed sequences of rock in the upper plate of the RMT (McFarlane, 1997).

The Strathearn Formation crops out in a number of small discontinuous bodies, mostly conglomerate, in the northern one-third of the SRF, where the upper contact is inferred to be the Coyote thrust. Only the lower part of the formation is present in the SRF, at most 50 m. In the BP, the Strathearn Formation is as much as 360–380 m thick (Theodore and others, 2003a). The provenance of conglomerate in the Strathearn is local. Recrystallization in the unit near the west edge of the SRF may be an effect of emplacement of the roughly 1.5-km-wide, 38-Ma informally named Hatter stock, which is present just to the west (Great Basin Gold, Ltd., Ivanhoe Project Report, December, 2001) (see also Wallace, 2003b). Previously, Hollister and others (1992) reported the Hatter stock to be 43 Ma.

Geologic relations of overlap assemblage rocks in the SRF and BP to rocks in the upper plate of the RMT have resulted in significant revisions of the timing of regional contractional tectonism. Previously, (1) the Antler orogeny was envisaged as having been completed by the Late Pennsylvanian; that is, prior to deposition of the Pennsylvanian and Permian Antler Peak Limestone (Roberts and others, 1958; Roberts, 1964; Dickinson, 2001), and (2) the next succeeding contractional tectonism to affect the Antler orogen is inferred to have been the Late Permian and/or Early Triassic Sonoma orogeny (Silberling and Roberts, 1962). However, our investigations in the Tuscarora Mountains and in the Shoshone Range (J.K. Cluer, written commun., 2000; see also Cluer and others, 1997) strongly suggest that during the middle Late Pennsylvanian to middle Early Permian a regional east- to southeast-directed thrusting or shortening event reactivated significant parts of the RMT allochthon. The Lander thrust in the Shoshone Range is envisaged by Cluer to have a formed a duplex with the middle Paleozoic RMT, and the Coyote thrust in the BP is (1) geometrically equivalent of the

Lander thrust, and (2) probably represents a late Paleozoic reactivation along a duplex thrust formed at the same time as initial emplacement of the upper plate of the RMT in the Tuscarora Mountains.

Late Paleozoic deformation of the Antler orogen previously had been referred to as the Humboldt orogeny (Ketner, 1977), and that orogeny was mainly envisioned as including epeirogenic uplift, as well as depression of a number of basins widespread throughout the Cordillera (Snyder and others, 2000). Both uplift and depression owe their origins primarily to development of the Ancestral Rockies (Dickinson, 2001). Regardless, well-documented shortening in the BP (Theodore and others, 2003a, 2004) involving the Strathearn Formation requires significant modification of earlier concepts of regional tectonism in this part of the Great Basin (see also Cashman and others, 2000, 2001; Trexler and others, 2004).

Jurassic Intrusive Rocks

Narrow, mostly northwest-striking dikes of hornblende lamprophyre and biotite (phlogopite)-bearing (Jbl) were emplaced into rocks as young as the Devonian Popovich Formation (Dp) in the lower plate of the RMT, and rocks as young as the chert unit (Dsc) of the Devonian Slaven Chert in the upper plate.

Miscellaneous Intrusive Rocks

Miscellaneous intrusive rocks in the SRF are volumetrically insignificant, and they include Jurassic or Tertiary altered diorite dikes or sills (TJd), an Eocene basaltic andesite dike (Tba), and a small number of Miocene rhyolite plugs and minor dikes (Tri). Altered diorite sills strike northeast near the Rodeo Creek mineralized occurrence, where they are possibly mineralized. In addition, emplacement of these rocks is believed to have been associated with much of the recrystallization in the general area of this mineralized occurrence (Theodore and others, 2003b). An altered diorite or dacite dike striking approximately N35°W also is present in the north and south high walls of the Sage Hen pit at the Rossi Mine. This pyrite-bearing fine-grained dike is near vertical and has a porphyritic texture of roughly 1-cm-wide calcic feldspar phenocrysts set in an altered groundmass. The dike is similar to Eocene dikes present farther to the southeast along the Carlin trend. Altered diorite dikes also crop out along the REN fault at the REN Mine in NW¼ sec. 12, T37N, R49E. At this locality the bulk of the near surface mineralized rock mined at REN included altered diorite (Albino, 1994). Approximately 22,000 oz Au was mined from this occurrence (table 1).

A single Eocene basaltic andesite dike (Tba) has been mapped in the SRF. This dike crops out at the Dee Mine where it forms prominent north-striking, irregularly distributed exposures along a high-angle fault between the chert subunit of the Rodeo Creek unit (Drc) and the Bootstrap limestone (DSb). The dike contains abundant fresh plagioclase microlites and olivine phenocrysts, some partly altered to calcite, set in a biotite-bearing, partly devitrified fine-grained groundmass (M.D. Ressel, oral commun., 2002). The apparent age of the dike, on the basis of $^{40}Ar/^{39}Ar$ on the matrix, is 37.6±0.3 Ma (Ressel, 2000; see also Henry and Ressel, 2000).

Rhyolite intrusions and minor dikes (Tri) are present in the Miocene rhyolite flow unit (Trf) of the Rhyolite of Antelope Creek. A small rhyolite intrusive body that straddles Antelope Creek in NW¼ sec. 29 and NE¼ sec. 30, T37N, R49E, is characterized by vertical flow banding that cuts surrounding gently dipping rhyolite flows. Sanidine that was separated from one sample obtained from the intrusive rhyolite body that straddles Antelope Creek (loc. 12) has been dated by $^{40}Ar/^{39}Ar$ methods. The apparent age is 15.01±0.08 Ma (table 2).

Rhyolite Flows

A thick pile of abundantly porphyritic rhyolite flows (Trf) crops out west of Antelope Creek near the west boundary of the SRF. The unit also includes some well-exposed, extremely fresh vitrophyre whose extent is shown by a hachured pattern on the geologic map. These flows are contiguous and correlative with the informally named Craig rhyolite of Bartlett and others (1991) that is mapped as unit Tcr by Wallace (2003b) in the Willow Creek Reservoir SE Quadrangle to the west. In the SRF, the highly resistant unit is composed of multiple, generally well-layered, gray porphyritic to porphyry, holocrystalline to vitrophyric, rhyolite flows that form bold outcrops. Locally, these rocks weather brownish red. Flow layers mostly are horizontal, but they also are contorted, in places yielding steep dips. In aggregate, the flows are more than 500 m thick near west edge of the SRF on the basis of a drill hole collared in S½ sec. 13, T37N, R48E (E.A. Lauha, oral commun., 2002). In the Willow Creek Reservoir SE Quadrangle, the rhyolite flows partly interfinger with unconsolidated deposits of the Miocene Carlin Formation (Bartlett and others, 1991). Sanidine that was separated from three samples (locs. 13–15) has been dated by $^{40}Ar/^{39}Ar$ methods. Apparent ages range from 15.15±0.08 to 14.99±0.08 Ma (table 2). The rhyolite flow unit is overlain by the silt, sand, and mudstone deposits including abundant tuff unit (Tcm) of the Carlin Formation west of Antelope Creek in SE¼ sec. 17, T37N, R49E.

Rhyolite of Boulder Creek

Miocene rhyolite of Boulder Creek (Trb) crops out only in a small area that is west of Boulder Creek and near the south edge of the quadrangle. The welded tuff, siltstone, and tuffaceous sandstone unit (Tct) of the Carlin Formation overlies the rhyolite of Boulder Creek. Sanidine that was separated from three samples of the rhyolite of Boulder Creek in the Rodeo Creek NW and NE Quadrangles, south and southeast of the SRF, has been dated by $^{40}Ar/^{39}Ar$ methods.

Apparent ages range from 14.97±0.05 to 14.91±0.04 Ma (table 2), slightly younger than the rhyolite flows of Antelope Creek. Rhyolite of Boulder Creek also is similar to parts of several rhyolite units in the Willow Creek Reservoir SE Quadrangle (Wallace, 2003b).

Miocene Carlin Formation

Largely unconsolidated Miocene gravel and silt deposits crop out mostly in the western half of the SRF where they are best exposed along moderately incised drainages and below local ledges of resistant tuff and sedimentary breccia within the unit. Miocene sediments in northeastern Nevada are part of the Humboldt Formation of Sharp (1939), and those sediments exposed near the town of Carlin, Nevada, were called the Carlin Formation by Regnier (1960). The latter name has been carried northward along the Carlin trend by numerous authors to informally refer to all Miocene sediments in the area, and that name is used in that context in this report. The Miocene Carlin Formation consists of four map units in the quadrangle: a basal welded tuff, silt, and tuffaceous sandstone unit (Tct), succeeded upwards by a silt, sand, and mudstone unit (Tcm), and followed by a silt and sand unit (Tcs). These three units are present in the southwest quarter of the quadrangle. The fourth unit is an undivided silts, sands, tuffs, and fanglomerate unit (Tcu) that crops out in the northern part of the quadrangle. Units Tcm and Tcs extend west into the Willow Creek Reservoir Quadrangle (Wallace, 2003b), though near the west edge of the SRF they probably include small areas of unmapped Quaternary unconsolidated deposits. The Miocene rhyolite flows in the Willow Creek Reservoir Quadrangle apparently were topographically higher than some of the sites of deposition of the Carlin Formation (Wallace, 2003b).

The tuff, silt, and tuffaceous sandstone unit (Tct) contains widespread drab gray-green, yellowish to pinkish brick-red quartz crystal tuff in a poorly exposed sequence of unconsolidated silt and some tuffaceous sandstone. The apparent age of the unit is 14.7±0.08 Ma, a date which nicely corresponds to the ages of the two underlying volcanic units Trf (15.15±0.08 to 14.99±0.08 Ma) and Tpr (14.97±0.05 to 14.91±0.04 Ma) (table 2; see above).

The silt, sand, mudstone, abundant tuff unit (Tcm) is mostly unconsolidated poorly exposed silt, sand, and mudstone, and includes some resistant 2- to 3-m-thick sedimentary breccias. Near the Rossi Mine, the Tcm unit includes angular boulders set in a tuffaceous matrix that grades (1) up section into silts and local gravels, and (2) laterally into mega-rippled fluvial tuffaceous sands and lacustrine clays. Sanidine that was separated from volcanic glass shards in 15 samples from 10 localities has been dated by $^{40}Ar/^{39}Ar$ methods (locs. 1-10, on the geologic map). Apparent ages range from 15.1±0.08 to 14.4±0.08 Ma (table 2). At REN, similar fracture coatings in the Carlin Formation are anomalous in gold, containing as much as 50 ppb Au.

A silt and sand unit of the Carlin Formation (Tcs) includes mostly unconsolidated, poorly exposed silt and sand, as well as widespread clay-rich areas. The unit crops out only in a several km^2 area near the southwest corner of the SRF where it is roughly 70 m thick.

An undivided silts, sands, tuffs, and fanglomerate unit of the Carlin Formation (Tcu) is present only in the northernmost part of the SRF.

Tertiary and Quaternary Unconsolidated Deposits

Tertiary and Quaternary unconsolidated deposits (units QTg_1 and QTg_2), typically gravels, are present mostly in the western part of the SRF where they form the outflow fans of a number of old channels that terminate in deeply incised canyons in the eastern parts of the quadrangle and in the BP to the east. Unit QTg_2 is the older of these two units and it caps a broad mesa in the southwest part of the quadrangle. Previously (Theodore and others, 1998, 2000a, 2000b), unit QTg_2 was assigned to an upper unit of the Carlin Formation. However, the base of the largely flat-lying deposits of unit QTg_2 near the southwest corner of the quadrangle has a slight angular discordance with underlying units of the Carlin Formation which appear to have been tilted slightly prior to deposition of QTg_2 (see cross sections B–B' and C–C'). Unit QTg_2 includes some truck-sized, well-rounded boulders that suggest significant transport in a very energetic medium. Unit QTg_2 in the SRF probably is the same well-dissected fan that extends as far north as the Toe Jam Mountain Quadrangle (Henry and Boden, 1999). On the basis of geomorphological expression, unit QTg_1 appears to have been reworked in many places from the older QTg_2 gravels. Nonetheless, assignment of undated, unconsolidated deposits to the proper unit is quite problematical and is subject to ongoing discussion, especially since the SRF also contains some Quaternary older alluvium (Qoa) and Quaternary older fanglomerate deposits (Qof).

Structural Geology

Structural development of supracrustal rocks in the SRF episodically spans the Paleozoic through Cenozoic Eras and includes multiple effects of periodic compression and extension. However, deep-seated and rifted Archean and Proterozoic crustal rocks (Kistler and Peterman, 1978; Burchfiel and others, 1992; Tosdal and others, 2000) also must have exerted a profound structural imprint on the structures we now see at or near the surface of the SRF. As summarized by John and others (2003), contractional deformation affected the margin of the continent during the Antler, Humboldt, Sonoma, Nevadan, Elko, Sevier, and Laramide orogenies. The middle Paleozoic Antler and late Paleozoic Sonoma orogenies placed eugeoclinal sedimentary rocks (Roberts Mountains and Golconda allochthons, respectively) eastward onto sedimentary rocks of the continental shelf. A foredeep basin and an overlap sequence developed mostly

east of the Antler highlands in the middle to late Paleozoic. The Nevadan and Elko orogenies took place in the Middle to Late Jurassic, the Luning-Fencemaker folding and thrusting in the Late Jurassic to Early Cretaceous, and the Sevier and Laramide orogenies in the Late Cretaceous to early Tertiary. These orogenic events reflect progressive contraction of the miogeocline from west to east. In northern Nevada, successive orogenies further displaced older allochthons, were often accompanied by translational movements, and usually were followed by intervening periods of relaxation, extension, or transtension. Extensional deformation largely has affected the region since the late Eocene.

Some district-scale tectono-stratigraphic patterns nonetheless have emerged. They include, from north to south, (1) a wide area underlain by Ordovician quartzarenite (Ovq) and related chert (Ovc) and silt (Ovs), all of the Vinini Formation in approximately the northern quarter of the SRF. The quartzarenite also includes some conglomeratic facies near the trace of the Coyote thrust. The Coyote thrust forms the sole of the structural block containing the quartzarenite, and the block also includes the structurally higher Squaw Creek thrust, a relatively minor thrust whose west-striking trace near the north edge of the quadrangle is covered entirely by Tertiary and Quaternary unconsolidated deposits. (2) A relatively thin structural wedge of the mélange unit (Dsm) of the Slaven Chert makes up the upper plate of the Little Jack thrust. This wedge crops out in the north-central and east-central part of the quadrangle and appears to form an antiform mostly with the underlying chert unit (Dsc) of the Slaven Chert at its core along the projected trace of the Carlin trend. (3) The lowermost allochthon of the RMT includes Ordovician shale and chert (Ovsc), which crops out most extensively near the southeast corner of the quadrangle, and Ordovician, Silurian, and Devonian siliceous rocks undivided (DSOu) that crop out along the east flank of Round Mountain. However, these siliceous rocks along the east flank of Round Mountain may belong to the Rodeo Creek unit.

As further pointed out by John and others (2003), linear "trends" of gold deposits, such as the northern part of the Carlin trend in the SRF, are thought to reflect deep crustal structural control on ore deposition (Shawe, 1991; Tosdal and others, 2000). As indicated on the geologic map of the SRF, long through-going, northwest-striking faults are not present. However, short northwest-striking faults and other district-scale surface features, such as the alignment of structural windows through the Roberts Mountains allochthon (Roberts, 1960, 1966) and zones of anomalous fold axes (Madrid and Roberts, 1991; Peters, 1996), may be expressions of deep transcurrent faults or other crustal structures as described above. Leonardson and Rahn (1996) suggest that post-Jurassic extension in the Betze-Post gold orebody bracketed mineralization was directed east-southeast and may have involved left-lateral movement on the Post fault. However, Berger and Theodore (2005) also have presented a case for a widespread, temporally and areally, SEDEX gold component in many Carlin deposits in Nevada. In addition, the trace of the 90-km-long north-northeast striking Crescent Valley-Independence lineament of Peters (2000) is present approximately 15 km east of the SRF and the lineament is inferred to have been a focus of lateral displacements that may range in age from late Paleozoic to middle Cenozoic. Peters (2000) envisions the Crescent Valley-Independence lineament as representing a zone of first-order sinistral deformation and fluid conduit that essentially was the driving mechanism for the escape of gold-bearing fluids into second-order structures along the Carlin trend. However, the Crescent Valley-Independence lineament may just as well represent a second order sinistral wrench-fault system related to first order deep-seated dextral displacements along the Carlin trend. Some north-northeast striking faults in the SRF are parallel to the Crescent Valley-Independence lineament. Thus, some lateral displacements along north-northeast-striking faults in the SRF may have occurred as reactivated minor splays related to the displacements along the lineament (see also Peters, 2003).

An ancestral Carlin trend—geometrically coincident with the present Carlin trend—may form a significant crustal boundary between (1) transitional crust southwest of the Carlin trend and (2) intact Proterozoic crust, transitional crust, and the Proterozoic Mojave crustal province northeast of the present-day Carlin trend on the basis of Sr and Pb isotopic data (Tosdal and others, 2000). In addition, Grauch and others (2003a) combine regional Sr and Pb isotopic data with magnetotelluric models to develop a new magnetic and gravity interpretation of the crustal structure of north-central Nevada (see also, Crafford and Grauch, 2002; Grauch and others, 2003b). In their model, the Carlin trend appears to be associated with two of three northwest-striking crustal boundaries that they identify. They further suggest that these crustal boundaries could have formed either as rift or transform faults during the late Proterozoic breakup of Rodinia or as faults accommodating lateral movements or accretion during later Paleozoic tectonic events.

In order to expedite discussion of the structural geology of the SRF, the area has been categorized into ten geologically coherent structural blocks (fig. 4).

Folds

Previous studies of folds in the region have shown that mesoscopic fold axes near gold deposits along the Carlin trend plunge at shallow angles to either the northwest or to the southeast (Peters, 1996). The orientation of these folds has been used by Peters (1996) to define a northwest-southeast structural domain that coincides largely with the inferred trace of the Carlin trend of gold deposits. Mesoscopic folds outside the northwest-southeast domain mostly plunge at shallow angles to the north-northeast or to the south-southwest (Evans and Theodore, 1978). The mesoscopic folds whose fold axes have north-northeast trends are inferred to have horizontal components of structural shortening that are compatible with an eastward direction of movement of the upper plate

of the RMT. However, geometric relations between north-northeast and northwest trending folds in the Dee structural block suggest that the northeast folds are younger than the northwest folds. In addition, many northeast-trending folds in this structural block are parallel to northeast striking thrust faults suggesting a temporal association between them.

Megascopic folds in the SRF are dominated by axial traces that are either north or northwest trending. Thus, they appear to be consistent with the previous regional studies cited in the preceding paragraph. Perhaps the best-documented megascopic folds with north trends are those that crop out in the general area of the REN Mine in NE¼ sec. 11, T36N, R49E. In this area, rocks of the Ordovician Vinini Formation, Silurian and Devonian Elder Sandstone, and Devonian Slaven Chert—all in the upper plate of the RMT—have been deformed into a number of similarly trending, tightly appressed, overturned to the east, anticlines and synclines. These folds plunge at shallow angles to either the north or the south. A number of parasitic mesoscopic folds are present on the limbs of the megascopic folds, but the mesoscopic folds have trends that diverge somewhat from the prominent north axial trends of the megascopic folds. In addition, a west-dipping thrust 0.5 km west of the REN Mine at the base of the Elder Sandstone is coplanar with axial planes of the overturned anticlines and synclines. This suggests a cogenetic relation between the thrust and the folds.

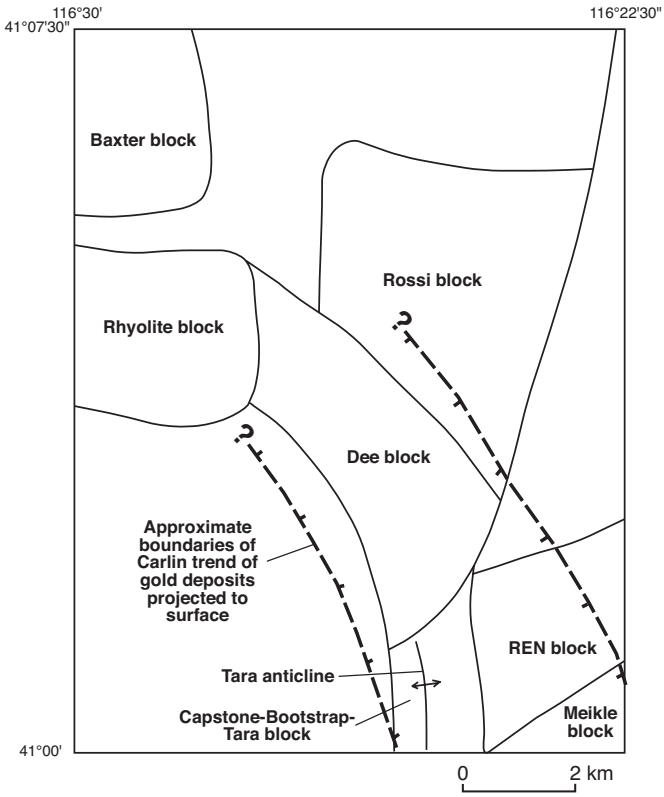

Figure 4. Structural blocks and approximate boundaries of the Carlin trend of gold deposits, projected to the surface, in the Santa Renia Fields Quadrangle, Nevada.

Major folds also are present near the Dee and Tara Mines. A prominent north trending overturned fold in the footwall of the Dee fault, approximately 1 km north of the Dee Mine suggests dextral-reverse movement on the Dee fault. The major megascopic fold in the upfaulted Capstone-Bootstrap-Tara block is the Tara anticline, whose hingeline has an approximate N15°W. axial trace along the west flank of the block (fig. 4). In the general area of the Dee Mine, axial trends of megascopic folds have (1) north trends—some folds are overturned to the east, others are overturned to the west, suggesting internal shortening of the upper plate of the RMT in this area; (2) northwest trends—approximately N30°W; and (3) northeast trends. The northwest orientation of folds is dominant in the south part of the Dee structural block, whereas in the north part, axial trends of megascopic folds are dominated by generally north to north-northeast fold trends. From a regional perspective, fold sets that have north axial trends are compatible with regional shortening in the allochthon associated with its emplacement during the middle Paleozoic.

A prominent megascopic anticlinal fold that is apparently overturned to the southeast formed in rocks of the Devonian Slaven Chert in NE¼ sec. 22, T37N, R49E and has an axial trend of approximately N80°E. Structural fabrics near the hinge of the fold at its westernmost exposures plunge to the southwest. As mapped, the axial trend of this fold approximately parallels the trace of (1) the Little Jack and Coyote thrusts that crop out roughly 1 km and 2 km, respectively, to the north, and (2) the Sink thrust fault that crops out approximately 0.5 km to the south. These faults probably were active sometime during middle Late Pennsylvanian and middle Early Permian (see above; Theodore and others, 2003a, 2004). Thus, the N80°E-trending fold is interpreted as having formed during late Paleozoic reactivation of the allochthon of the RMT, as is the prominent northeast-trending structural wedge of Elder Sandstone, marked by the Sink thrust at the base of the wedge, a few hundred meters south of the fold. West-northwest-striking and northeast-dipping faults and similarly oriented folds in the Betze-Post gold orebody, approximately 2 km south of the southeast corner of the SRF, also may have formed during late Paleozoic shortening (Bettles, 2002).

A number of other folds—some overturned, others upright—have northeast axial trends that are parallel to the traces of thrust faults in the Dee structural block. These folds probably formed syntectonically with the shortening that was involved in development of the thrust faults. In addition, they are at a high angle to a northwest elongate axis of a domal arch (see below) that coincides with the Carlin trend. Because of this relation, the folds with the northeast axial trends are inferred to predate development of the arch.

A poorly defined broad open antiformal fold or domal arch trending about N30°W appears to be coincident with the Carlin trend in the SRF. This domal arch perhaps is the most important fold in the quadrangle because of its spatial coincidence with much of the trace of the Carlin trend in the quadrangle and it appears to be plunging to

the northwest. The domal arch is manifested by a broad curvature of bedding attitudes in Slaven Chert from north-northeast strikes and northwest dips in the single exposure of its southwest limb near Antelope Creek to roughly east-northeast strikes and north dips in the mélange unit of the Slaven Chert in its northeast limb generally north of the Rossi Mine. In addition, the mélange unit of the Slaven Chert appears to be wrapped around the domal arch. In the uplifted Capstone-Bootstrap-Tara block (fig. 4), the hinge line of the arch is somewhat more tightly constrained—that is, along the trace of the Tara anticline—than the arch farther to the northwest near the Dee Mine. The coincidence of the domal arch with the inferred trace of the Carlin trend suggests that structural development of the arch may have enhanced ground preparation for later fluids associated with the main gold mineralization. Madrid and Roberts (1991) assigned a Middle Jurassic age to northwest-trending fold hinges and culminations in the region and further suggested that these hinges and culminations were responsible for windows of lower plate rocks presently exposed through the upper plate of the RMT. Tension gashes also appear to have developed along the hinge of the domal arch and these are filled by narrow dikes of Jurassic biotite lamprophyre (Jbl) whose strikes parallel the long axis of the domal arch. Evans and Theodore (1978) noted that the average axial fold trend related to the middle Paleozoic Antler orogeny in the southern Tuscarora Mountains is approximately N20°E.

Thrust Faults

As described above, a number of important thrust faults are present in the SRF. These thrust faults apparently are stacked and include the Roberts Mountains thrust, the Sink thrust, the Little Jack thrust, the Coyote thrust, and the Squaw Creek thrust, as well as a number of other relatively minor thrust faults. The middle Paleozoic Roberts Mountains thrust crops out only at the Dee Mine. However, the Roberts Mountains thrust has been encountered by numerous drill holes in a broad area north of the Dee Mine (see cross section D–D'). The traces of the late Paleozoic Little Jack, Coyote, and Squaw Creek thrusts are extensive in the northern half of the quadrangle. The latter three faults generally strike east and show steep dips at the surface that progressively shallow to the north with increasing depth. They are probably correlative with the Lander thrust in the Shoshone Range (Theodore and others, 2003a). As suggested by Theodore and others (2003a, 2004) from geologic relations in the BP, the Little Jack thrust probably is slightly older and structurally lower than the Coyote thrust. In addition, significant imbricate thrust faults associated with the Little Jack thrust include the Rossi and the Sink thrust faults that strike northeast in the central part of the SRF. Because of a well-developed shear zone along the Rossi thrust, major thrust displacements may have occurred along the latter structure rather than the former in this general area. This would imply that some segments of the trace of the Little Jack thrust were piggybacked on slightly later major offsets along the Rossi thrust.

The structurally highest thrust fault assigned a name in the quadrangle is the Squaw Creek thrust, which is apparently buried by Tertiary and Quaternary unconsolidated sediments near the north edge of the SRF. This thrust is believed to represent a minor imbricate thrust fault related to the subjacent Coyote thrust system. However, note that the short, approximately 0.1-km-long thrust near the northeast corner of the SRF is not a continuation of the Squaw Creek thrust to the northeast. This short unnamed thrust segment, covered by the Miocene Carlin Formation (unit Tcu), is structurally higher than the Squaw Creek thrust as shown in the BP (Theodore and others, 2003a).

High-angle Normal Faults and Reverse Faults

A large number of high-angle normal and a few high-angle reverse faults are present in the SRF. Many of these faults have north strikes and are apparently related to Tertiary extension that has been prominent in the region since the Eocene. Minor local high-angle reverse separations along some high-angle faults may result from a dominant scissors-type displacement along most of the faults' strike lengths. Perhaps the most conspicuous of high-angle faults are north-striking faults that bound and uplift the Capstone-Bootstrap-Tara block (fig. 4). Syndepositional normal movement on the Dee fault, down on the west, is suggested by thickness changes in Devonian rocks, units DSb and Drc, across the fault at the Dee Mine. Although the Dee fault is a high-angle fault, its projection onto cross section D–D' dips shallowly to the west because of the acute angle of intersection between the line of section and the fault trace. Farther to the north in the general area of the Rossi Mine, the Dee fault appears to have been reactivated well into the Miocene because it cuts unit Tcm of the Carlin Formation. Syndepositional normal movements in the Miocene also appear to have occurred along a number of normal faults that bound the Carlin Formation in the quadrangle. Other prominent north-striking high-angle faults in the Dee structural block include the BW and Hinge faults.

The Post and REN faults are important faults near the southeast corner of the SRF. North of the Bell Creek fault in the REN structural block, the trace of the Post fault is approximately 350 m east of the REN fault. Farther to the south near the southeast corner of the quadrangle, the Post fault appears to cut the Antimony lineament, an important ore-controlling structure in the Meikle gold mine. The strike of the Antimony lineament parallels the projected trace of the Carlin trend. In addition, the Antimony lineament is an important ore-controlling structure in the Meikle gold mine. Even farther to the southeast near the Betze-Post orebody (fig. 2), the Post fault has a shift in strike approximately every 2,000 m, the geometry of which suggests that relative offset along it is left lateral (Leonardson and Rahn, 1996). The Post fault system is the predominant feeder zone for gold-mineralizing fluids at the Betze-Post orebody (Volk

and others, 1996). The latest movements along the REN and Post faults are quite young, inasmuch as they postdate the Miocene Carlin Formation.

When the Carlin trend is considered in its entirety in the SRF, large numbers of through-going, high-angle, northwest-striking faults do not coincide with a regional northwest alignment of mineralized occurrences. Two minor exceptions are the northwest striking fault and co-parallel Jurassic and/or Tertiary dike at the Rossi Mine and the Antimony lineament at the Meikle Mine. Nonetheless, the absence of large numbers of through-going, northwest-striking faults in the quadrangle is quite striking and appears to confirm the conclusion of Howard (2003) that no major single Cenozoic structure controls the northwest orientation of the Carlin trend. Grauch and others (2003a) propose that supracrustal rocks near the trend may be detached from crustal rocks at depth that might contain first-order northwest-striking structures. The latter structures might have acted as channels for mineralizing fluids and their possibly associated magmas during the Eocene (Arehart and others, 2003). Nonetheless, the Post and Dee faults both appear to be quite complex old faults that (1) are shallow expressions of the underlying zone of weakness along the Carlin trend, and (2) record multiple episodes of tectonism. Both of these faults, as well as many of the other north-striking faults in the quadrangle, may be indicative of en-echelon extensional arrays atop the fundamental, deep-seated zone of weakness along the Carlin trend. Finally, the non-parallelism of Jurassic biotite lamprophyre dikes in the Dee and Capstone-Bootstrap-Tara structural blocks suggests that counterclockwise rotation of the Dee block may have occurred as a result of translational right lateral components of offset along the Boulder fault.

Discussion

Strathearn Formation

One of the most important units to crop out in the SRF is the middle Late Pennsylvanian and middle Early Permian Strathearn Formation, even though its area of outcrop is quite minimal in the quadrangle. Conglomerates belonging to the Strathearn Formation represent submarine fanglomerates derived mostly from a largely southeastwards advancing allochthonous sheet of quartzarenite of the Ordovician Vinini Formation (Berger and others, 2001; Theodore and others, 2003a, 2004). The structural sole of this allochthonous lobe is inferred to be the Coyote thrust. A middle Early Permian upper conglomerate unit, the highest unit recognized in the Strathearn Formation, as well as similarly aged dolomitic siltstone, onlap directly onto quartzarenite that comprises the allochthon of the Coyote thrust in the BP (Theodore and others, 2003a, 2004). Chert fragments in the conglomerates were derived mostly from Devonian Slaven Chert, including a widespread thick mélange unit of the Slaven in the footwall of the Coyote thrust.

Widespread geologic evidence in the BP to the east indicates that the allochthon of the RMT was reactivated sometime following initial deposition of a middle Late Pennsylvanian lower conglomerate unit of the Strathearn Formation (Theodore and others, 2003a, 2004). Such contractional reactivation, including that reflected in the SRF by the Coyote thrust and two of its related contractional structures, the Little Jack thrust and the Squaw Creek thrust, as well as a number of other named and unnamed thrust faults, probably occurred in conjunction with extensive late Paleozoic tectonism in western North America associated with the Ancestral Rocky Mountains (see also, Dickinson, 2001; Barbeau, 2003). The latest phases of deformation during the Early Permian in the Ancestral Rocky Mountains may have involved transform slip along the California-Coahuila transform (Dickinson and Lawton, 2003). The timing of this latter deformation appears to be compatible with the timing of late Paleozoic shortening documented in the SRF and BP.

Rocks Deep Below the Carlin Trend

Previously proposed factors that may have contributed to the distribution of the gold deposits at the mining district scale include (1) presence of early SEDEX gold in the region (Berger and Theodore, 2005), (2) distribution of favorable carbonate facies—best represented mostly by the Popovich Formation—in the lower plate of the RMT (Armstrong and others, 1997, 1998), and (3) orientation of the Paleozoic continental margin (Tosdal and others, 1998).

As suggested by Emsbo (1999, 2000), Emsbo and others (1999, 2003), and Berger and Theodore (2005), synsedimentary SEDEX gold accumulations in the Great Basin might have been a Paleozoic precursor event in many Carlin-type gold deposits. The origins of such early paragenetic gold subsequently are masked by multiphase Mesozoic and Cenozoic tectonism and magmatism. Comparative examination of the settings of 25 Carlin-type deposits in Nevada that appear to have strong synsedimentary affiliations shows a steady southward stratigraphic ascent of mineralized sequences from Upper Ordovician and Lower Silurian rocks to Early and Late Mississippian rocks (Berger and Theodore, 2005). This stratigraphic ascent involves an inferred mineralizing time span from 460 to 325 Ma, possibly related to a Paleozoic heat source localized along a failed, amagmatic, propagating rift.

In addition, many have proposed that the presence of steep, deeply penetrating structures along the Carlin trend may have led to concentration of Eocene magmas and hydrothermal fluids that, in turn, provided the bulk of the introduced gold (Henry and Ressel, 2000). However, no major Cenozoic fault or system of faults has been found to act as a unifying structure to connect the gold deposits that are aligned approximately N30°W along the northern Carlin trend. Nor is there a widespread presence of Eocene magmatic rocks in the SRF. Geologic relations well away

from the trend, however, may have some relevance. Rocks currently exposed in the metamorphic core complex of the Ruby Mountains, Nevada, approximately 70 km to the southeast, probably are representative of middle crustal level rocks in the general area of the Carlin trend (Howard, 2003). As further pointed out by Howard (2003), the middle crustal rocks are comprised of complexly folded and thrusted nappes and tectonically interleaved wedges of Archean and Proterozoic rock. Such relations most likely would obscure the expression of any steep deeply penetrating structure as has been proposed previously by Rodriguez (1998), Crafford and Grauch (2002), and Grauch and others (2003b). The ambiguous relations among gold-mineralized rock, Eocene magmas, and through-going northwest faults in the SRF thus may be the result of the geologically diffuse boundary between mid-crustal and upper crustal rocks in this part of the Carlin trend. Such a diffuse boundary should contribute to an increased importance for minor fault splays in the final residency of any introduced gold, as well as more widespread occurrences of the actual gold deposits.

Analysis of the Miocene Carlin Formation

The Miocene (Fleck and others, 1998) Carlin Formation of Regnier (1960) crops out widely in the western part of the SRF where unconsolidated basal units of the formation were deposited on Miocene rhyolite flows (Trf)—the informally named Craig rhyolite of Bartlett and others (1991)—and the rhyolite of Boulder Creek (Trb). In addition, the Tcm unit of the Carlin Formation has been deposited on various Paleozoic formations throughout the quadrangle. The formation also includes mineralized fragments of rock derived from the Carlin trend. The Carlin Formation and the volcanic rocks merit additional discussion because they cover the projected trace of the Carlin trend in the SRF.

Reported age estimates of about 14.4 Ma to 15.1 Ma (table 2)—not including those samples that may have some contamination—for air-fall tuffs of the Tcm unit of the Carlin Formation permit a wide variety of potential source areas of silicic tuffs in northern Nevada, southeasternmost Oregon, and southwesternmost Idaho (Luedke and Smith, 1981; 1982; 1983; 1984). This overall potential source area commonly is referred to as the Orevada volcanic province, which includes peralkaline and metaluminous rhyolites (Perkins and others, 1998). Further, the Carlin Formation tuffs in the SRF belong to the white metaluminous vitric tuff compositional group of Miocene tuffs established in the northern Basin and Range Province by Perkins and others (1998). Volcanic rocks similar in age to the tuffs in the SRF are abundant in the Snowstorm and Sheep Creek Mountains to the west (Luedke and Smith, 1984), and calderas probably do not exist there (C. Henry, written commun., 2004). Volcanic centers that represent known sources of pyroclastic materials include the McDermitt, Lake Owyhee, and the Owyhee-Humboldt volcanic fields. Ages of 16.1 to 15.0 Ma are reported by Rytuba and McKee (1984) for the major ash-flow tuffs of the McDermitt center. The tuff of Whitehorse Creek, from the Whitehorse caldera, the youngest of the McDermitt calderas, yielded an age of 15.0±0.3 Ma (Rytuba and McKee, 1984), similar to older ages determined in unit Tcm. Rytuba and Vander Meulen (1991), however, report ages of 15.5 to 15.0 Ma for ash-flow tuffs of the Lake Owyhee volcanic field and ages from about 16 to 13.8 Ma are reported by Ekren and others (1984) for the older volcanic rocks of the Juniper Mountain volcanic center on the Owyhee Plateau, but younger ages are dominant to the east (Perkins and others, 1995).

Despite the limited chemical variation in volcanic glass of the tuffs in unit Tcm of the Carlin Formation, correlation with other ashes and identification of their source requires study of the chemistry and age of more proximal ashes whose sources can be ascertained. Current results permit some observations and interpretations, however. The low Mg and Ca contents of the glass and a paucity of mafic minerals in the tuffs (Fleck and others, 1998) are compatible with either peralkaline or subalkaline magmas. The low-K content of the alkali feldspars from the tuffs is consistent with more alkalic sources rather than metaluminous sources. Total alkalies (Na_2O plus K_2O) and aluminum of glass shards in unit Tcm indicate a generally subalkaline magmatic character (Fleck and others, 1998), although the alkali contents in bedded ash layers may be subject to substantial diagenetic modification. The molecular $(Na_2O+K_2O)/Al_2O_3$ of the tuffs is quite constant at about 0.90, however, suggesting that alteration has not produced significant effects. The peralkaline character of the McDermitt and Lake Owyhee volcanic fields, however, makes those areas less likely as possible sources of the tuffs, although a substantial number of the analyses from the McDermitt field are subalkaline. The Lake Owyhee field contains both peralkaline and metaluminous tuffs, according to Rytuba and Vander Meulen (1991). However, analyses of rhyolites of the Juniper Mountain volcanic center (Ekren and others, 1984) group tightly with those of the Tcm tuffs, providing the best fit with available data (Fleck and others, 1998; see also, Perkins and others, 1998; Perkins and Nash, 2002). Nonetheless, all of the foregoing is contingent on an absence of diagenetic leaching of Na_2O from the glass shards in unit Tcm in the SRF—we cannot prove the latter.

The spatial and temporal relationship of epithermal and hot-springs-generated ore deposits in the northern Great Basin to magmatic and hydrothermal activity has been documented by field and geochronologic studies of many deposits in nearby mining districts (McKee and others, 1974; Silberman and others, 1976; Noble and others, 1988; Wallace and others, 1990). Noble and others (1988) summarize evidence for mineralization throughout the 17- to 14-Ma period in this region. West of the SRF, sedimentary strata correlated with the Carlin Formation overlie volcanic rocks thought to postdate mineralization at the Hollister Mine in the Ivanhoe Mining District (McKee and others, 1974; Wallace, 2003a). Locally within the SRF, however, some sequences of the Carlin Formation are themselves cut by low temperature quartz-adularia±Mn oxide veins as described above. Near

the west edge of the SRF, these veins are present as fracture and fragment coatings within the Tcm unit of the formation. Rhyolite flows and hypabyssal domes that appear to postdate some of the Carlin Formation west of the SRF show evidence of weak to strong alteration (Wallace, 2003a), and support the continuation of at least limited mineralization—mostly mercury—during and/or post sedimentation of the Carlin Formation. At Ivanhoe, for example, parts of 14.92-Ma rhyolite porphyry domes are silicified, as are rhyolite flows and overlying Carlin Formation in the general area of the Hatter stock (A.R. Wallace, written commun., 2003). Further, the area of the SRF resides in a region with currently elevated geothermal waters on the basis of the high temperatures of the groundwaters presently being extracted during pumping associated with active mining operations.

The stream-sediment geochemistry of the Carlin Formation in the SRF appears to be related, in part, to the presence of altered and mineralized pre-Tertiary rock along the Carlin trend (Theodore and others, 2003b). Furthermore, a "shoulder" of high values for a mineralization factor (Theodore and others, 2003b) may reflect concentrations of a number of metals in the Carlin Formation, mainly arsenic, that probably were derived from bedrock sources containing mineralized fractures exposed during the Miocene. The concentration of arsenic in the Tcm unit of the Carlin Formation is as much as 30 ppm As when the Carlin trend is approached from the west. This increase implies that the elevated abundance of arsenic in the Carlin Formation owes its origins to immediately adjacent rock comprising the altered halo of the Carlin trend. Mineralized and/or altered rock fragments probably have been shed directly into the sedimentary basin of the Carlin Formation, and migration of arsenic also may have occurred in the supergene environment of present-day gulleys after material was further recycled out of the Carlin Formation (Theodore and others, 2003b). Thus, elevated concentrations of arsenic in unconsolidated sediments of the Carlin Formation that cover part of the northernmost Carlin trend in the SRF can be traced directly back to their sources in arsenic-anomalous rock along the trend. At the Gold Quarry and at the Betze-Post deposits, tuffaceous gravel of the Carlin Formation present in local grabens is enriched in gold owing to the presence of gold-bearing clastic material derived from nearby exposed mineralized bedrock (J.B. Harlan and E. Lauha, oral communs., 2000). In addition, basal gravels in the Carlin Formation at the Mike deposit, approximately 25 km to the southeast of the SRF along the Carlin trend, locally contain gold-bearing clasts (Norby and Orobona, 2002).

Concentrations of many other elements apparently are high in the Carlin Formation in the SRF (Theodore and others, 2000b) relative to their contents in nearby Paleozoic rocks, and they include the following elements with the approximate mean value of their contents shown in parentheses: Co (7 ppm), Mn (500 ppm), Zn (80 ppm), Fe (2.5 weight-percent), Th (10 ppm), Sr (200 ppm), Ca (> 1 weight-percent), La (50 ppm), Mg (0.8 weight-percent), Al (6 weight-percent), Na (1 weight-percent), K (2 weight-percent), Zr (100 ppm), Y (20 ppm), Nb (20 ppm), Be (2.5 ppm), and Sc (6 ppm). However, many of these concentrations in the Carlin Formation are less than elemental abundances in ordinary sedimentary rocks (see also, Tan and Chi-lung, 1970; Taylor and McLennan, 1983; McLennan and Taylor, 1984). High concentrations of some elements partly reflect an igneous component such as abundant alkali feldspar and abundant glass shards throughout the unit (Fleck and others, 1998). Thus, present-day metal concentrations in the Carlin Formation are derived from a wide variety of sources of different ages, including unmineralized Paleozoic bedrock, mineralized Paleozoic bedrock, Miocene rhyolite flows and the rhyolite of Boulder Creek, post 14.4-Ma hydrothermal fluids that deposited chalcedony, opal, and adularia in the formation, and 15.1- to 14.4-Ma sanidine-rich air-fall tuff.

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