GEOLOGIC OVERVIEW OF THE CARLIN TREND GOLD DEPOSITS

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INTRODUCTION

The Carlin trend in northeastern Nevada forms the largest and most productive accumulation of gold deposits in North America. Teal and Jackson (1997b) reported a gold endowment that by the end of 1996 included past production, reserves, resources, and mineral inventory of over 107 million ounces (3,330 t [metric tons]). More than 40 separate deposits have been delineated since disseminated gold mineralization in carbonate host rocks was first discovered by Newmont geologists John Livermore and Alan Coope in 1961. From their original discovery, a classification for this style of gold mineralization has come to be referred to as "Carlin-type" deposits. By early 2002, more than 50 million ounces (1,560 t) of gold had been recovered on the Carlin trend from 26 separate operating or past producing mines. Open-pit mining began in 1965 at the Carlin Mine, and underground mining began in 1993 on the same deposit.

The scope of this paper is to present a regional geologic setting of the Carlin trend. As part of the concluding discussion, a spectrum of Carlin trend deposit types is categorized to illustrate the relative influence of structural and stratigraphic controls on each deposit.

REGIONAL GEOLOGIC SETTING

The Carlin trend is a 38-mile (60-km) long north-northwest alignment of predominantly carbonate-hosted gold deposits located in northeastern Nevada (figs. A-1 and A-2, plate 1), within the Basin and Range physiographic province of the western United States. Gold deposits are generally hosted in a variable stratigraphic package of Ordovician through Lower Mississippian rocks. Within specific deposits, however, Cretaceous and Tertiary dike swarms and the Jurassic-Cretaceous Goldstrike granodiorite stock constitute up to 15% of the mineralized material.

Regional Tectonic Development

Regional stratigraphic and Sr isotopic data indicate that northeastern Nevada was situated along a stable paleo-continental margin during much of the Cambrian through Early Mississippian (Stewart, 1980). During this period, a westward-thickening, prism-shaped package of sediments was deposited from the outer margins of the paleo-continental shelf into an adjacent oceanic basin. Within this depositional environment, sedimentary facies graded from eastern miogeoclinal to western eugeoclinal sequences.

During Late Devonian through Middle Mississippian time, compressional tectonism associated with the Antler orogeny resulted in regional-scale folding and east-directed imbricate thrusting of the western eugeoclinal assemblage of

predominantly siliciclastic rocks over the eastern autochthonous assemblage of silty carbonate rocks. This thrust surface is preserved regionally in north-central and northeastern Nevada and is referred to as the **Roberts Mountains thrust** from its type location, 50 miles (80 km) south of the Carlin trend (Roberts and others, 1958). The resultant accretionary mass formed the emergent Antler highlands, which in turn shed an eastern-directed overlap assemblage of clastic rocks during the Middle Mississippian to Early Pennsylvanian (Smith and Ketner, 1975).

Subsequent late Paleozoic tectonism during Early to Middle Pennsylvanian time (Humboldt orogeny) was followed by deposition of shelf carbonate sequences during Middle Mississippian to Early Pennsylvanian (Smith and Ketner, 1975; Ketner, 1977). A third period of resumed uplift and folding, possibly related to the Early Triassic Sonoma orogeny, was followed by yet another period of eastward-directed folding and thrusting during the Early Cretaceous Sevier orogeny (Stewart, 1980). All of these successive periods of compressional tectonism contributed to the regional structural complexity prior to the mineralizing event(s) that formed the Carlin trend gold deposits. Geologists debate whether the effects of the earlier Antler orogeny or the later Mesozoic deformation and intrusive activity resulted in the formation of broad amplitude, N25–35°W-trending, northerly plunging anticlines within autochthonous carbonate assemblage rocks that are now preserved in uplifted tectonic windows along the Carlin trend (Roberts, 1960; Evans, 1974a). From north to south these include the **Bootstrap, Lynn, Carlin**, and **Rain** tectonic windows. All Carlin trend gold deposits discovered thus far occur within or proximal to these tectonic windows (fig. A-1).

The current regional physiography is the manifestation of Tertiary extensional tectonics. The inception of pre-Basin and Range extension and crustal thinning is interpreted to have begun during the late Eocene (37–40 Ma) with the onset of regional magmatism (Christiansen and Yeats, 1992, p. 291; Wright and Snoke, 1993). Tensional, generally east-west directed, Basin and Range tectonism is interpreted to have begun during the early Miocene (17–20 Ma) (Evans, 1980), although the timing of its inception remains a subject of debate. The north-northwest regional alignment of the Carlin trend gold deposits reflects an apparent preexisting zone of crustal weakness that transects present-day, generally north-trending Basin and Range topography.

Sedimentary Rocks

Gold deposits on the Carlin trend are hosted in lower Paleozoic sedimentary rocks that are subdivided into three major packages: 1) an autochthonous shelf to outer shelf carbonate and clastic sequence (eastern assemblage rocks); 2) an allochthonous, predominantly eugeoclinal sequence (western assemblage rocks); and 3) a Late Mississippian overlap assemblage (host to gold mineralization in the Rain area).
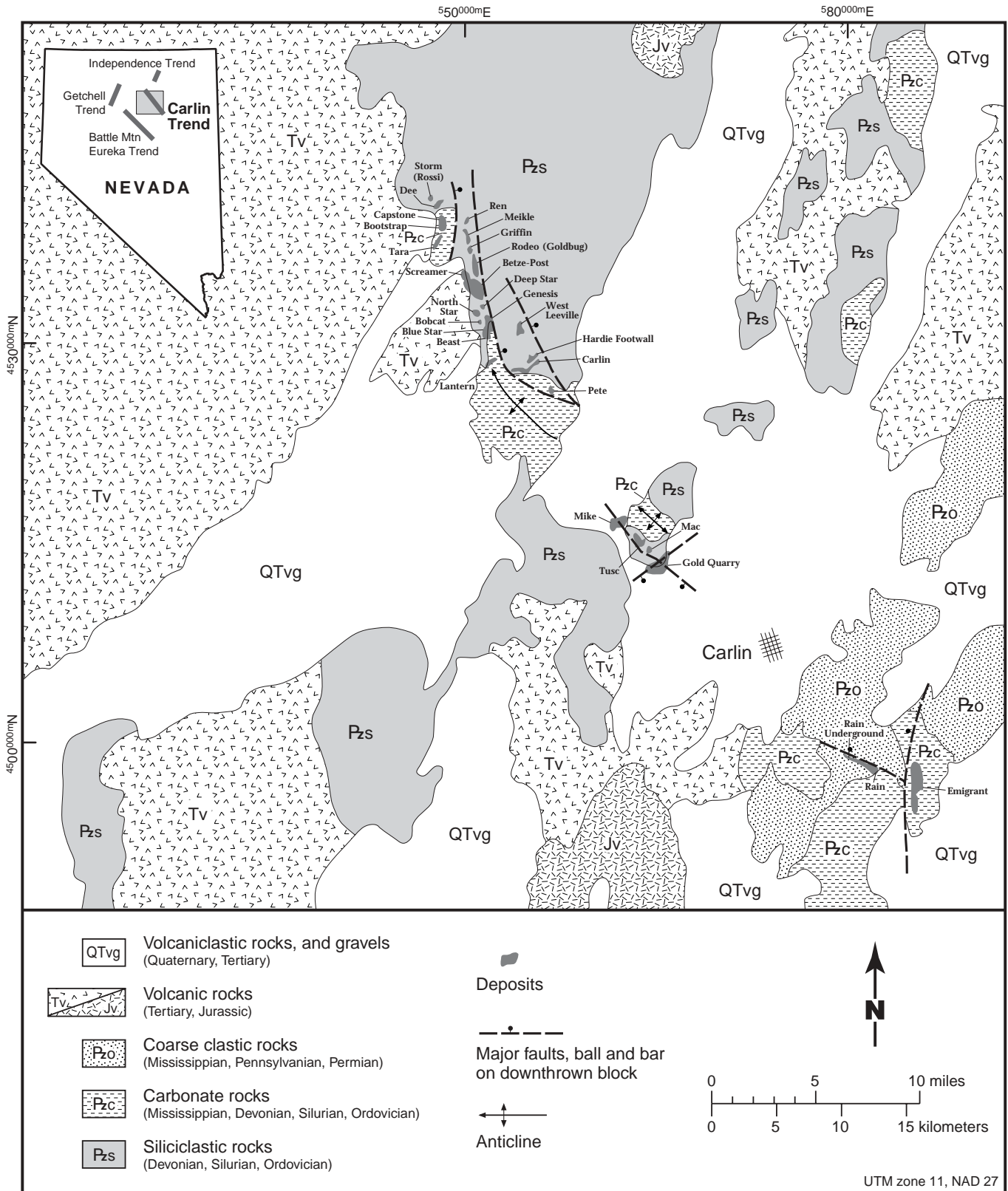
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[1]Newmont Mining Corporation

Figure A-1. Simplified geologic map of the Carlin trend, Nevada.

Independence Trend

Getchell Trend

Carlin Trend

Battle Mtn Eureka Trend

NEVADA

550 000mE

580 000mE

4530 000mN

4500 000mN

Tv

Jv

QTvg

Pzc

Pzs

Storm (Rossi)

Dee

Capstone

Bootstrap

Tara

Screamer

North Star

Bobcat

Blue Star

Beast

Lantern

Ren

Meikle

Griffin

Rodeo (Goldbug)

Betze-Post

Deep Star

Genesis

West Leeville

Hardie Footwall

Carlin

Pete

Pzc

Mike

Mac

Tusc

Gold Quarry

Carlin

Pzo

Pzc

Rain Underground

Rain

Emigrant

QTvg

QTvg

Pzs

QTvg | Volcaniclastic rocks, and gravels (Quaternary, Tertiary)

Tv Jv | Volcanic rocks (Tertiary, Jurassic)

Pzo | Coarse clastic rocks (Mississippian, Pennsylvanian, Permian)

Pzc | Carbonate rocks (Mississippian, Devonian, Silurian, Ordovician)

Pzs | Siliciclastic rocks (Devonian, Silurian, Ordovician)

Deposits

Major faults, ball and bar on downthrown block

Anticline

0   5   10 miles

0   5   10   15 kilometers
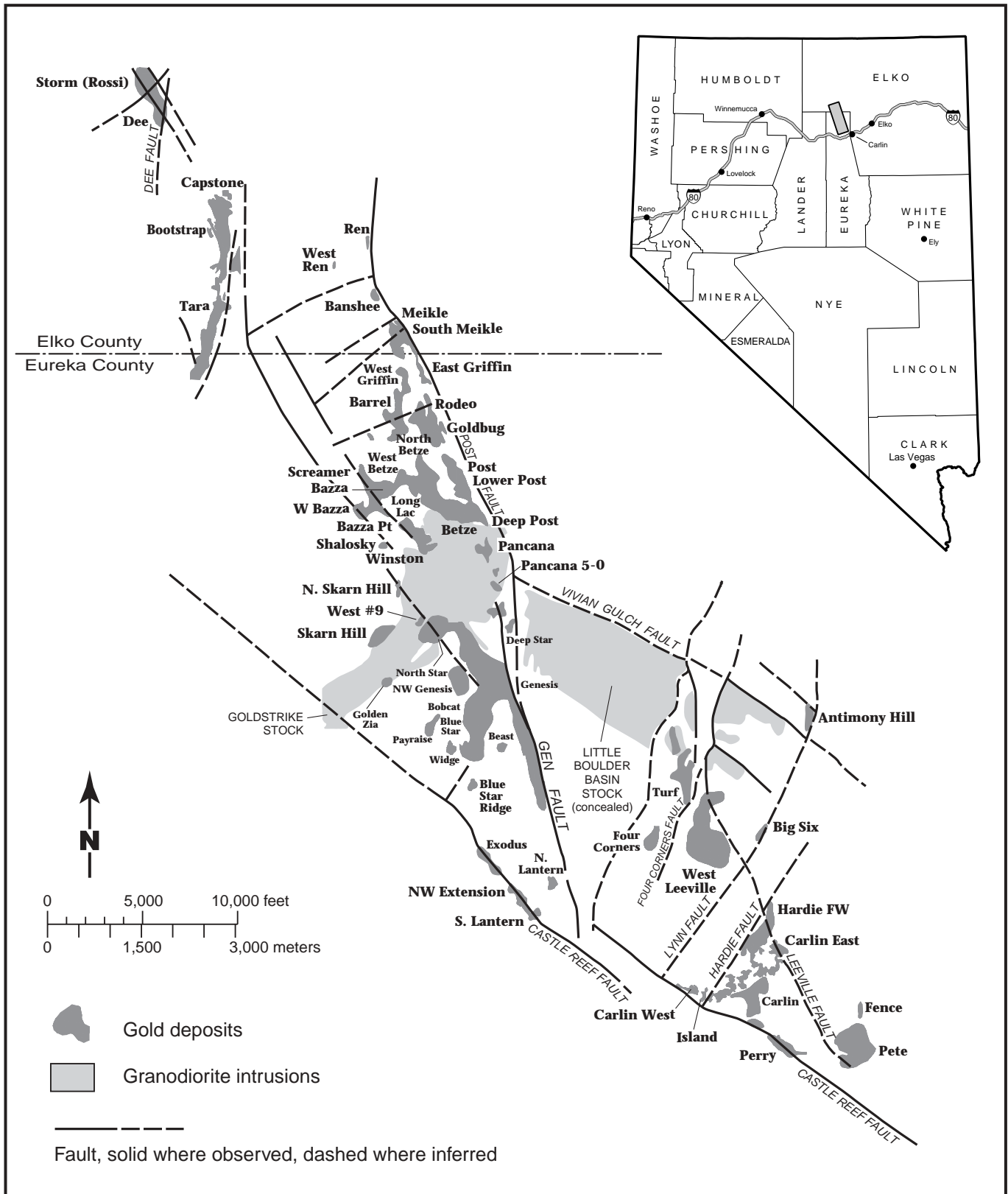
UTM zone 11, NAD 27

N

10

Figure A-2. Gold deposits, northern Carlin trend, Nevada. *Modified from Teal and Jackson, 1997b.*

AUTOCHTHONOUS ROCKS

The autochthonous sequence is host to the majority of gold deposits on the Carlin trend, with most occurring in the upper 1,300 to 1,700 feet (400 to 500 m) structurally beneath the Roberts Mountains thrust (fig. A-3).

Roberts Mountains Formation

Evans (1980) described the Devonian-Silurian Roberts Mountains Formation as a 1,540-foot (470-m) thick sequence of medium- to thin-bedded, platy, laminated silty limestone to dolomitic siltstone. The upper 435 feet (130 m) of the Roberts Mountains Formation is the most favorable for gold mineralization. Geologists have come to recognize this section as an upper facies containing intercalated, thin bioclastic sedimentary debris flows and silty limestone with irregular "wispy" laminations (Koehler, 1993; Moore, 1994). This wispy texture is interpreted to have formed as a result of bioturbation and soft sediment compaction that, along with intercalated fine-grained debris flow beds, resulted in an increased permeability for later gold-bearing fluids. The Roberts Mountains Formation is host to such gold deposits as **Carlin, Betze, West Leeville, Pete, Screamer, Deep Post, Goldbug-Post,** and **Mike**. The contact with the overlying Popovich Formation is gradational.

Popovich Formation

From its type section 2 miles (3 km) west of the Carlin Mine, Evans (1980) described the Devonian Popovich Formation as a 130-foot (400-m) thick variable sequence of micrite, silty limestone, and fossiliferous limestone. From the abundance of drill data in the northern Carlin trend, the Popovich is recognized as a unit that undergoes a sharp facies change from thin-bedded silty limestone and micrite in the Carlin and Genesis-Blue Star Mine areas, to massive, fossiliferous, sparry limestone beds in the Meikle, Bootstrap-Capstone, and Storm (Rossi) deposits, 8 to 10 miles (12 to 15 km) to the northwest. The Popovich Formation and equivalent rocks are host to gold deposits at **Betze-Post, Genesis-Blue Star, Gold Quarry (Deep West), Meikle, Goldbug-Rodeo, Deep Star, Bootstrap-Capstone,** and **Dee-Storm** (fig. A-2).

Rodeo Creek Unit

Depositionally overlying the Popovich Formation is a 170- to 840-foot (50- to 250-m) thick sequence of intercalated siliceous mudstone, thin bedded siltstone and calcareous siltstone (Ettner, 1989). As part of the autochthonous eastern facies sedimentary package, the Rodeo Creek is recognized by geologists in the northern and central Carlin trend as the upper transitional zone that occurs immediately beneath western facies eugeoclinal sedimentary rocks of the Roberts Mountains allochthon. The lower contact of the Rodeo Creek unit was originally misinterpreted from field exposures to represent the sole of the Roberts Mountains thrust. Portions of the upper Rodeo Creek unit are, however, interpreted as para-allochthonous due to the imbricate nature of the thrust's surface. Indeed, conodonts from the Rodeo Creek have been interpreted as Late Devonian to Early Mississippian (Ettner, 1989), indicating the unit is correlative with allochthonous Woodruff Formation in the Rain Mine area of the southern Carlin trend (northern Piñon Range). The silty facies of the Rodeo Creek unit is a receptive host to the upper portions of giant gold deposits at **Gold Quarry** (Rota, 1995) and **Upper Betze-Post** (Thoreson, 1993). In both instances, these large gold-bearing systems stoped through weakly permeable basal siliceous mudstone and into the upper silty portions of the unit.

ALLOCHTHONOUS ROCKS

The allochthonous sequence is host to dominantly high-angle, structurally controlled and sheeted, vein-style gold deposits. Due to the complexity of this accretionary mass, rock types have been lumped into a single "super" formation, summarized as follows.

Vinini Formation

This allochthonous eugeosynclinal sequence consists of easterly directed, imbricated thrust sheets of predominantly Lower Ordovician to Middle Silurian sedimentary chert, mudstone, siliceous mudstone, and minor greenstone (Merriam and Anderson, 1942; Roberts and others, 1967; Stewart, 1980). Finney and others (1993) recognized that the lower imbrications in the allochthon also contain Middle Devonian carbonate strata. All of these rock types are present along the northern and southern Carlin trend (Tuscarora Mountains) as a complexly intercalated, folded, and imbricated mass. The Vinini Formation contains an estimated cumulative thickness in excess of 5,000 feet (1,500 m). On the Carlin trend, this sequence is host to smaller high-angle fault-controlled and vein deposits such as **Capstone, Big Six, Fence,** and **Antimony Hill** (figs. A-2 and A-3).

OVERLAP ROCKS

An overlap sedimentary sequence consisting of coarsening upward Middle to Late Mississippian strata is present only on the southern portion of the Carlin trend (Piñon Range), where it is host to gold deposits at **Rain Open Pit, Rain Underground,** and **Emigrant**. Mudstone of the basal Webb Formation grades upward into sandstone and conglomerate of the Chainman Formation. The Webb-Chainman sequence is underlain by thick-bedded limestone of the autochthonous Middle Devonian Devils Gate Formation and structurally overlain by allochthonous, Middle to Late Devonian siliciclastic mudstones, cherts, and siltstones of the Woodruff Formation (Mathewson, 1993; Mathewson and Jones, 1994). Gold mineralization at the Rain and Emigrant deposits is hosted within a brecciated contact zone at the base of the Webb Formation and extends as collapse breccia pipe bodies into the underlying Devils Gate Formation (Mathewson and Jones, 1994).

INTRUSIVE ROCKS

Three periods of intrusive activity, in the form of north-northwest-trending dike swarms and stocks occur along the Carlin trend, indicating the belt of gold deposits were formed
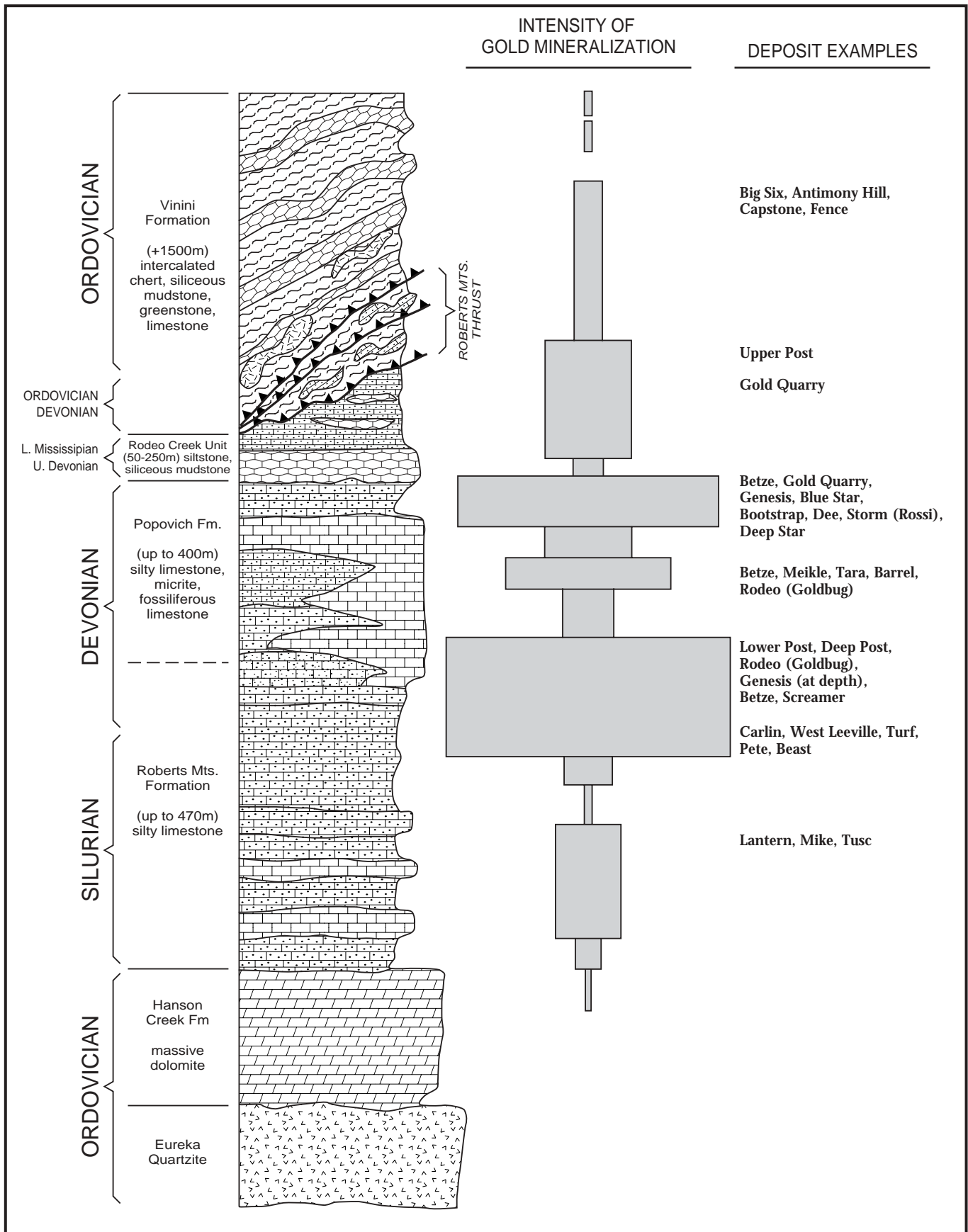
INTENSITY OF
GOLD MINERALIZATION

DEPOSIT EXAMPLES

ORDOVICIAN

Vinini
Formation

(+1500m)
intercalated
chert, siliceous
mudstone,
greenstone,
limestone

*ROBERTS MTS.
THRUST*

ORDOVICIAN
DEVONIAN

L. Mississipian
U. Devonian

Rodeo Creek Unit
(50-250m) siltstone,
siliceous mudstone

DEVONIAN

Popovich Fm.

(up to 400m)
silty limestone,
micrite,
fossiliferous
limestone

SILURIAN

Roberts Mts.
Formation

(up to 470m)
silty limestone

ORDOVICIAN

Hanson
Creek Fm

massive
dolomite

Eureka
Quartzite

**Big Six, Antimony Hill,
Capstone, Fence**

Upper Post

Gold Quarry

**Betze, Gold Quarry,
Genesis, Blue Star,
Bootstrap, Dee, Storm (Rossi),
Deep Star**

**Betze, Meikle, Tara, Barrel,
Rodeo (Goldbug)**

**Lower Post, Deep Post,
Rodeo (Goldbug),
Genesis (at depth),
Betze, Screamer**

**Carlin, West Leeville, Turf,
Pete, Beast**

Lantern, Mike, Tusc

Figure A-3. Idealized stratigraphic column and gold mineralization, northern and central Carlin trend, Nevada.

within a zone of anomalous heat flow. Episodic magmatism began in the Late Triassic and continued through the late Tertiary (Evans, 1980; Arehart and others, 1993; Ressel, 2000). Arehart and others (1993) reported a [preferred] $^{40}Ar/^{39}Ar$ age of 158 Ma for the Goldstrike stock (fig. A-2). Contact metamorphism around the Goldstrike stock has resulted in calc-silicate marble and quartz hornfels development within adjacent sedimentary rocks. A metamorphic aureole extends 170 to 670 feet (50 to 200 m) along the northern margin of the Goldstrike stock, within the Betze-Post deposit (Leonardson and others, 1995), and as much as 2,700 feet (800 m) beyond its southern margin within the Genesis-Blue Star deposit (Schutz and Williams, 1995).

Associated with the Goldstrike intrusive event is a belt of Jurassic-Cretaceous dike swarms of intermediate to mafic composition, present throughout the Carlin trend. These dikes were later altered and locally sulfidized, and as such, provide a maximum age to mineralization. Mineralized Tertiary dikes with $^{40}Ar/^{39}Ar$ dates of 38 to 39 Ma (Emsbo and others, 1996; Ressel, 2000a) further constrain a maximum age. As a general observation, dike swarms intruded along the same structural zone of weakness that later served as channelways for gold-bearing fluids. Thus, on a regional scale, the north-northwest alignment of gold deposits exhibits a strong spatial relationship to the general north-northwest trend of dike swarms.

Cropping out along the central Carlin trend, between the Pete and Mike deposits, are the Richmond and Welches Canyon stocks. The Richmond stock is a uniformly textured, quartz monzonite, with a reported Middle Cretaceous K/Ar date of 106 Ma (Evans, 1980). The Welches Canyon stock is a multi-phased rhyolite to granodiorite (Thompson, 1995), with a K/Ar age of 37.8 Ma (Evans, 1974a) and a more recent $^{40}Ar/^{39}Ar$ date of 38.4 Ma (Ressel and others, 2000a). Smith and Ketner (1975) reported K/Ar dates of 35 to 37 Ma on the Bullion granodiorite stock located 6 miles (10 km) south of the Rain open-pit deposit.

Structural Controls of Gold Deposits

The north-northwest alignment of the Carlin trend deposits is not in itself a manifestation of any singular fault zone, but rather a combination of structural features in a zone of crustal weakness and sustained high heat flow, as indicated by multiple periods of intrusive activity. This environment created a setting conducive to prolific gold mineralization. While structural influences differ between deposits on a regional scale, common features include:

- High-angle, northwest-striking fault sets that served as primary fluid conduits and are commonly filled by lamprophyric and monzonitic dikes;

- High-angle northeast-striking faults that served as secondary conduits, particularly at structural intersections with northwest faults;

- Broad to moderate amplitude anticlinal folds in autochthonous carbonate rocks; and

- High-angle and stratabound, premineral stage, collapse breccia bodies.

NORTHWEST FAULTS

North- to northwest-striking faults form the primary conduits to gold deposition in every mining subdistrict on the Carlin trend (table A-1). This influence is reflected in the geometry of individual deposits and the multiple alignment of deposits along major feeder faults (fig. A-2). This structural fabric can be subdivided into three principal sets: N15–30°W, N45–60°W, and north-south. All three sets are commonly dike-filled within or proximal to gold deposits. Throw across individual faults or fault zones ranges from less than 170 feet (50 m) to more than 2,700 feet (800 m).

In the northern Carlin trend, Kofoed and Vance (1995) mapped and modeled the north-striking Bootstrap fault as the primary control of mineralization in the Bootstrap-Capstone deposit. Volk and others (1995) described the lower main zone of mineralization at the Meikle deposit as having a strike length of 1,200 feet (360 m) that trends N20–30°W in the immediate footwall of the Post fault. Thoreson (1993) described the Post fault as a primary control to the general N25°W trend of the Post deposit. Leonardson and Rahn (1995) later described the northwest-trending JB-3 fault, which parallels the Post fault, as the primary control of the North Betze deposit. Schutz and Williams (1995) described the N10°W Genesis fault and the N45°W Reindeer fault as primary controls in the Genesis-Beast and the Northwest Genesis-North Star deposits, respectively. In the central Carlin trend, the Lantern, West Carlin, and Perry (Peregrine) deposits are aligned along the N50°W strike of the Castle Reef fault. In the south-central Carlin trend, Rota (1993) described the alignment of the Gold Quarry-Little Hope-Tusc-Mike deposits as occurring along the strike of the N40°W Good Hope fault, at structural intersections with successive northeast-striking cross faults. In the southern Carlin trend, Mathewson and Jones (1994) and Longo and others (1996) described the Rain Underground deposits as occurring within the immediate hanging wall of the N60°W strike of the Rain fault or along the hanging-wall-parallel Galen fault (Williams and others, 2000).

Major northwest faults such as the Post, Genesis, Castle Reef, Leeville, and Good Hope have complex kinematics, frequently displaying evidence of multiple stages of recurrent normal, oblique, and apparent strike-slip movement. This characteristic tends to obscure their role as gold-bearing fluid conduits. For example, the latest observed movement on the Post fault displaces the postmineral Miocene Carlin Formation (Thoreson, 1993). Putnam and McFarland (1990) first proposed that a regional northwest structural fabric displayed along the Carlin trend is the manifestation of dextral wrench fault kinematics developed during the evolution from an early Tertiary transpressional tectonic environment within the western United States. In a structural analysis of the Leeville fault east of the Carlin Mine, Cole (1989) documented evidence of 2,050 feet (625 m) of apparent dextral displacement. While Putnam's genetic model accommodates the observed en echelon pattern of primary northwest and secondary northeast-striking cross faults, it is likely that these structural trends were superimposed over an earlier zone of crustal weakness, as indicated by Cretaceous-age dike swarms that occupy both fault sets. Newmont and Barrick geologists in the northern Carlin

trend have observed abrupt subsurface carbonate basin facies/ shoal facies boundaries in autochthonous eastern assemblage gold-bearing host rocks, which can be interpreted to reflect northwest-trending paleo-carbonate basin escarpments inherited from Devonian-Silurian time (Teal, 1995; Volk and others, 1995).

Table A-1. Examples of Carlin trend gold deposits that exhibit primary northwest structural control.

Deposit	Controlling Fault
Bootstrap-Capstone	Bootstrap fault-N–S (Koefoed and Vance, 1995)
Meikle (Lower Main)	Post fault-N20–30°W (Volk and others, 1995)
Post	Post fault-N20–30°W (Thoreson, 1993)
North Betze	JB-3 fault-N35°W (Volk and others, 1995)
Screamer	Buzzard fault-N20°W
Genesis-Beast	Genesis fault-N10°W (Schutz and Williams, 1995)
NW Genesis-N. Star	Reindeer and #9 faults N30°W (Schutz and Williams, 1995)
North Lantern	Castle Reef fault N50–60°W
West Carlin	Castle Reef fault (Radtke, 1985)
Gold Quarry	Good Hope fault-N45°W (at intersection with NE Chuckar-Alunite faults) (Rota, 1995)
Tusc	Good Hope fault (Rota, 1993)
Mike	Good Hope fault (Arkell, 1993; Teal and Branham, 1997)
Rain/Rain Underground	Rain fault-N60°W (Mathewson, 1993; Mathewson and Jones 1994; Williams and others, 2000)

NORTHEAST FAULTS

Northeast-striking faults play an important role for focusing gold mineralization at the deposit scale, particularly at intersections with northwest-striking faults (examples include the Gold Quarry, Mike, and Meikle deposits). Rarely are northeast faults important dike-filled structures. Notable exceptions include the K and Anne dikes in the Genesis Mine (Paul and others, 1993), the Hardie fault in the Carlin deposit (Moore, 1994), and the West Bounding fault in the West Leeville deposit. In general, throw across individual northeast-striking faults ranges from tens of feet to over 1,700 feet (500 m) along the Gold Quarry (Chuckar-Alunite) fault system (Rota, 1993).

Steve Moore documented the importance of northeast-striking faults as gold-bearing conduits in the discovery of Newmont's Hardie Footwall deposit in 1993. Moore's deposit

model demonstrated the importance of the immediate footwall of northeast-trending horst blocks as structural fluid traps. The application of this exploration model led to the discovery of Newmont's West Leeville deposit in 1994. Here, mineralization occurs in the footwall of the north-northeast-striking West Bounding fault (Jackson, 1995). This setting is also interpreted in the Goldbug deposit, where high-grade gold mineralization (≥0.20 opt [troy ounces per short ton] or 6.9 g/t) occurs in a north-trending horst block bounded by the northeast-striking Hillside and northwest-striking Post faults (Jory, 1995).

FOLDS

Generally northwest-trending, broad to moderate amplitude, anticlinal folds play an important role as structural traps to fluid migration within individual deposits and on a regional scale. Cole (1993) proposed that autochthonous carbonate sequences that form the Carlin and Lynn tectonic windows are remnant segments of a larger north-northwest-trending regional-scale anticline, with a doubly plunging fold axis that extends from the Gold Quarry deposit northward to the Genesis deposit. In this unified tectonic window model, gold deposits of the north-central and south-central Carlin trend are clustered along both the northeast and southwest flanks of the anticline, while its central portion has been segmented into a Tertiary, postmineral graben by late-phase Basin and Range extensional block faulting.

On a deposit scale, moderate amplitude folds play an important role as structural traps to gold-bearing fluids. Volk and others (1995) described two sets of northwest-trending anticlines that control the distribution of higher-grade mineralization in the Betze-Post pits. The Betze anticline has a N50–60°W-trending fold axis that is subparallel to the northern margin of the Goldstrike pluton. The fold is interpreted to have formed as a result of compressive shortening related to the emplacement of the pluton (Leonardson and Rahn, 1995). It subsequently served as a structural trap for fluids that were ponded adjacent to the intrusive contact to form the Betze deposit. The second fold set, exposed in the eastern portion of the Betze-Post pit, is the more common N30°W trend of the Post anticline, located in the footwall of the Post fault (Thoreson, 1993). The crest of the fold localizes the geometry of stratiform gold mineralization in the Upper Post and Lower Post deposits. Immediately south of the Goldstrike pluton, Schutz and Williams (1995) described higher grade gold mineralization in the Genesis deposit as being controlled in part along the hinge zone of the N10°W-trending, northerly plunging Tuscarora anticline along the southern and deep extensions of the deposit.

PRE-ORE BRECCIA BODIES

Much has been written describing a wide spectrum of mineralized breccia textures from deposits on the Carlin trend (Radke, 1985; Kuehn, 1989; Bakken, 1990; Williams, 1992; Rota, 1993; Teal and others, 1994; Cole, 1995; Mathewson and Jones, 1995; Volk and others, 1995; Teal and Jackson, 1997b). However, within a number of individual deposits, the

formation of pre-ore stage, high-angle and stratabound breccia bodies contributed to the fluid dynamics of the later gold-bearing event. Volk and others (1995) documented a classic example of this phase in the Meikle deposit. In the Rain Underground deposit, Mathewson and Jones (1995) described pre-ore stage decalcification along the Rain fault zone in the underlying Devils Gate Limestone as resulting in the formation of pre-ore collapse breccias both within the limestone and the overlying Webb Formation mudstone. This process enhanced the permeability along the contact zone for subsequent gold-bearing fluids, in what otherwise would have been an unreceptive host rock. On the other hand, Williams (1992) and Williams and others (2000) believe that the bulk of the Rain breccias are hydrothermal in origin because the dolomitization in the underlying Devils Gate Limestone is quite restricted in distribution. These heterolithic breccias extend well beyond the extent of the underlying dolomitization with accompanying dissolution breccias. Alunite within the collapse breccias is related to supergene processes (Williams and others, 2000).

Gold mineralization is also selectively focused within coarse sedimentary debris flow horizons of the lower Popovich and upper Roberts Mountains Formations. This style of mineralization is particularly common in a series of deposits in the northern Carlin trend proximal to the carbonate facies transition that demarks a change from massive fossiliferrous limestone to micritic and silty limestone (Armstrong and others 1997). Thoreson (1993) and Leonardson and Rahn (1995) described the higher-grade gold mineralization in the Lower and Deep Post deposits as occurring within sedimentary debris flow facies of the lower Popovich Formation. Jory (this publication) describes high-grade (≥0.20 opt [6.9 g/t]) clast-supported collapse-breccia zones that overprint the same sedimentary debris flow breccias. Kunkle and Teal (1995) described this same style of mineralization in the nearby Barrel deposit (fig. A-2).

Alteration and Gold Mineralization

Numerous papers describe wall-rock alteration of the Carlin trend deposits, including classic studies by Hausen (1967), Hausen and Kerr (1968), Radtke (1985), Kuehn (1989), and Bakken (1990). Pervasiveness and intensity of alteration varies both within and between gold deposits, depending on magnitude of the mineralizing system, nature of the host rock, and density of structural conduits. Cuffney and Mallette (1992) summarized the salient features that characterized Carlin-type deposits:

- carbonate dissolution;

- silicification, particularly within structural conduits;

- argillic alteration of primary silicate minerals;

- gold-enriched sulfidation of reactive iron in host rocks, to form gold-bearing sulfide minerals (pyrite, arsenical pyrite, marcasite, arsenical marcasite);

- Multi-phase fluid inclusions, characterized by low salinity (0.5–7 wt % NaCl equiv.), variable amounts of CO_2, and low homogenization temperatures (120–250°C).

CARBONATE DISSOLUTION

Carbonate removal, in the form of decalcification (calcite removal) and more advanced decarbonatization (calcite/dolomite removal), is the most pervasive style of alteration observed within the Carlin trend deposits. As a general observation, the extent of carbonate dissolution is controlled partially by the composition of the original host rock. In deposits such as Meikle, Bootstrap, and Rain, hosted within or above dense, biosparitic limestone protolith, decalcification tends to be restricted around high-angle paleo-fluid conduits and laterally along abrupt compositional changes in strata. In deposits such as Carlin and West Leeville, decalcification is more pervasive and intense due to the original porosity and permeability of the host rock.

In the Carlin deposit, studies by Kuehn (1989) and Bakken (1990) describe acidic, hydrothermal fluid channeling along high-angle structural conduits and favorable statigraphic horizons that resulted in pre-ore stage decalcification, loss in density, and an increase in porosity and permeability of the host rock. The degree and intensity of carbonate removal ranges widely between mineralizing systems, and does not always exhibit a clear zonal relationship with gold deposition. Thoreson (1993) and Leonardson and Rahn (1995) describe total decarbonatization in the Betze and Lower Post deposits. However, satellite deposits to the Betze-Post system, such as the Goldbug (Jory, 1995) and Screamer deposits (fig. A-2), exhibit zones of higher gold grades that are only weakly decalcified.

ARGILLIC ALTERATION

Argillic alteration assemblages formed typically as a residual product of carbonate dissolution and acid attack of detrital silicate minerals. It is particularly well developed within deposits hosted in silty limestone or calc-silicate hornfels protoliths. Detrital clays and K-feldspar, present in small amounts (3–5%) of the silty limestone protolith, are altered to montmorillonite, kaolinite, illite, and/or minor sericite.

SILICIFICATION

The extent of silicification differs between types of deposits and, similar to carbonate removal, its importance as an alteration product is partially controlled by the composition of host rock. In deposits hosted in dense, biosparitic limestone or calc-silicate protolith (examples include the Meikle and Deep Star deposits), fluid permeability is more restricted to high-angle, structural conduits. As a result, silicification is locally more intense and spatially associated with gold mineralization. Rota (1993) described quartz as the most abundant alteration product in the Gold Quarry deposit, occurring throughout all stages of pre-ore to post-ore alteration. Volk and others (1995) described at least five stages of silicification in the Meikle deposit: **1) early pre-ore** metamorphic quartz veins associated with the emplacement of Jurassic intrusive rocks; **2) late pre-ore** silica replacement associated with early stage carbonate dissolution; **3) main stage ore** silicification occurring as episodic pulses, open-space fillings and veinlets associated with precipitation

of fine grain pyrite and gold; **4) post-ore** chalcedonic vug fillings and coatings; and **5) very late stage**, outwardly zoned quartz veinlets in siliciclastic rocks of the Vinini Formation that form a nonmineralized cap above the deposit.

In those deposits in which stratigraphy exhibits a dominant control (examples include Carlin, West Leeville, Hardie Footwall, and Screamer) fluid migration was more passive in nature and silicification within the ore zone is less significant. Silicification is focused along bioclastic debris horizons and proximal to fluid conduits, where it occurs peripheral to the main ore zone. In the Carlin deposit, Bakken (1990, p. 141) interpreted early stage acidic hydrothermal fluids as evolving into thermal equilibrium through a process of groundwater mixing. In this restricted model, silica continued to remain in equilibrium until the late-ore to post-ore stages of the hydrothermal system. It was then precipitated as pressure-temperature conditions waned. In whole rock analyses from the Carlin deposit, Kuehn and Rose (1992) documented a linear relationship between carbonate dissolution (CO_2 removal) and an increase in SiO_2. This relationship illustrates that the intensity of silica addition, beyond isochemical enrichment (~67% SiO_2), is more prevalent in dense carbonate hosted deposits, or as selective replacement in more calcite-rich and permeable bioclastic debris flow beds, due to their initially higher calcite content.

Kuehn and Rose (1992) also documented early, pre-ore stage deposition of barite-sphalerite-galena in the Carlin deposit. At the West Leeville deposit, the Popovich Formation is silicified, barren in gold, and strongly anomalous in base metals above the ore zone (Jackson, 1995; Jackson and Lane, 1997). Williams (1992) and Shallow (1999) documented pre-ore barite-sphalerite at Rain. These relationships suggest an early stage of silica and base metal deposition occurred in more passive, strata-controlled gold deposits.

GOLD MINERALIZATION

Gold in the Carlin trend deposits occurs as submicron particles (50–200Å) primarily within the lattices of pyrite and arsenian pyrite (Hausen and Kerr, 1967; Radtke, 1985; Bakken, 1990; Arehart and others, 1993a; Sha, 1993). Fluid inclusion studies by Kuehn (1989) in the Carlin deposit and Hofstra and others (1991) in the adjacent Jerritt Canyon district suggest gold was transported as a hydrogen bisulfide complex. Because fluid inclusion analyses exhibit consistent low salinities (1–7% NaCl equiv.) and enrichment in both H_2S and CO_2, gold-bearing fluids that formed the Carlin trend deposits are interpreted as an evolved fluid chemistry, a result of mixed meteoric-magmatic fluids origin. Thus, enriched H_2S concentration in the ore fluid resulted in sulfidation of reactive iron in the host rock to precipitate gold-bearing arsenian pyrite. Due to high CO_2 content in fluid inclusions, Kuehn (1989) estimated a depth of formation for the Carlin deposit to be on the order of 2.8±1.2 miles (4.4±2.0 km), within a temperature range of 180 to 245° C.

ALTERATION ZONING PATTERNS

The variations in alteration zoning patterns between individual gold deposits are a function of the magnitude and/or intensity of the gold-bearing system, and composition and density of the host rock, and, in some deposits, effects of a premineral, 158-Ma thermal metamorphic event. The majority of earlier alteration studies and descriptions in the literature (Hausen and Kerr, 1968, Radke, 1985; Kuehn, 1989; Bakken, 1990) focused on the Carlin deposit, one of the more strata-controlled, passive end-member style of deposits. In contrast, zonation patterns for silica-sulfide breccia pipes such as Deep Star (Harvey, 1990; Clode and others, this volume) and Meikle (Volk and others, 1995) exhibit compact envelopes in which silicification and sulfidation are more intensely focused.

Owing to observed differences and adaptation of the zonation pattern proposed by Kuehn and Rose (1992) the general alteration progression includes the following major, **distal-to-proximal** alteration assemblages for gold deposits on the Carlin trend:

1. **limestone:** calcite + dolomite + illite + quartz + K-spar + pyrite

2. **weak to moderate decalcification (dolomite halo):** dolomite ± calcite + illite ± kaolinite + pyrite ± gold;

3. **strong decalcification:** dolomite + quartz + illite ± kaolinite + pyrite ± gold

4. **decarbonatization:** quartz + kaolite/dickite + pyrite ± gold.

DISCUSSION

With a current gold endowment of greater than 100 million ounces (3,110 t) (Teal and Jackson, 1997b) and discoveries that have continued to increase this resource, the Carlin trend remains the most productive gold belt in North America. Carlin trend geologists informally acknowledge three components necessary for the formation of a gold deposit as including a range of interactions involving **strength of the hydrothermal system, structure**, and **host rock**. Within this context, those major geologic parameters that have contributed to the genesis of gold deposition on the Carlin trend include:

1. reactive and highly permeable carbonate host rocks;

2. a geologically long-active zone of crustal weakness originating along a paleo-continental margin, with development of major through-going fault systems; and

3. a regional tectonic environment of crustal thinning, with multiple intrusive episodes and sustained high levels of heat flow, which resulted in

4. multiple episodes of hydrothermal activity.

Age of Deposits

The age of gold mineralization along the Carlin trend continues to be a topic of debate. More recent [40]Ar/[39]Ar dates from altered, gold-bearing dikes by Emsbo and others (1996) on the Betze-Post and Ressel and others (2000a) on the Beast deposit have constrained what appears to be the primary period of gold mineralization in the northern Carlin trend to late Eocene (~36–40 Ma). Much of the remaining uncertainty is related to the

difficulty of obtaining reliable dates on minerals that are clearly of hydrothermal origin within the deposits. Given this uncertainty, the age of gold deposition is constrained by the presence of gold mineralization within both Jurassic-Cretaceous and Tertiary dikes, and the Miocene age of the postmineral Carlin Formation.

Dates on alteration minerals from many of the deposits yield Middle to Late Cretaceous ages ranging from 95 to 140 Ma. In the Carlin deposit, Kuehn (1989) reported K/Ar dates of 120 to 123 Ma from sericite in altered and mineralized dikes. In the Betze-Post deposit, Arehart and others (1993b) reported a 117 Ma age for gold mineralization, based on multiple $^{40}Ar/$ ^{39}Ar and K/Ar dates on sericite, with no evidence of significant hydrothermal activity younger than 110 Ma. Drews (1993) reported three K/Ar dates ranging from 95 to 97 Ma from hydrothermal illite in high-grade (≥0.20 opt [6.9 g/t] gold) ore samples within the Genesis and Blue Star deposits. In the Mike deposit, Teal and Branham (1997) reported two K/Ar dates of 107 and 111 Ma from a gold-bearing, K-feldspar flooded, altered dike in the Good Hope fault and from K-feldspar flooded, decalcified silty limestone protolith of the Roberts Mountains Formation, respectively.

Multiple Tertiary-age intrusions along the Carlin trend and Tertiary-age dikes within specific deposits in the northern Carlin trend indicate the influence of a younger, gold-bearing hydrothermal event that occurred in the late Eocene, around 40 Ma. Emsbo and others (1996) reported a $^{40}Ar/^{39}Ar$ date of 39 Ma from biotite in a gold-bearing dike in the Betze-Post deposit. Most recently, Henry and Ressel (2000) and Ressel and others (2000a, b) have reported $^{40}Ar/^{39}Ar$ dates from sericite ranging from 36 to 40 Ma on altered, gold-bearing dikes in the Post and Genesis fault zone. These dike swarms all occur within the Beast, Genesis, Griffin, and Meikle deposits in the northern Carlin trend. A single comparison of K/Ar and $^{40}Ar/$ ^{39}Ar dates from the same altered dike in the Genesis deposit suggests that the potential effect of thermal resetting of K/Ar dates yields a younger age. Schutz and Williams (1995) reported a 27 Ma K/Ar date on the altered, gold-bearing K dike in the Genesis deposit; Henry and Ressel (2000) reported a 39 Ma $^{40}Ar/^{39}Ar$ date from the same altered dike.

The authors interpret this information as supporting evidence for at least two and possibly three distinct periods of gold mineralization on the Carlin trend related to separate Mesozoic and Tertiary thermal events. Some of the K/Ar and $^{40}Ar/^{39}Ar$ dates are suggestive of Cretaceous ages for mineralization. More isotopic dating is needed, particularly of minerals that clearly formed during gold mineralization, before we can conclude that essentially all gold was deposited in response to the Eocene magmatic event. A third, younger mid-Miocene-age gold-bearing event occurred along the north-northwest projection of the Carlin trend deposits. At the Hollister Mine in the Ivanhoe district, 7.5 miles (12 km) north-northwest of the Dee Mine, epithermal gold mineralization is hosted in mid-Miocene (14–15.5 Ma) rhyolitic to dacitic volcanic rocks of the Tuscarora volcanic field (Henry and others, 1999). These rocks unconformably overlie mineralized Valmy and Vinini Formation siliciclastic rocks of the Roberts Mountains allochthon.

At the Gold Quarry deposit, in the central Carlin trend, Heitt (1992) reported K/Ar dates ranging from 28 to 27 Ma from supergene alunite veins that crosscut and postdate gold mineralization. Thus, gold deposition in the central Carlin trend was terminated prior to its initiation along what can be interpreted as its northwesternmost projection at the Hollister Mine. In summary, when viewed on a district-wide scale, multiple ages suggest that as a pattern, gold mineralization can be interpreted to have followed a multi-episodic, generally north-northwesterly progression over a constrained interval beginning with a minor period of gold and base-metal emplacement during late Cretaceous time and continuing major periods of emplacement during late Eocene and mid Miocene. The range and style of gold mineralization between deposits and the magnitude of the mineralizing systems that created the Carlin trend are consistent with the regional evidence of a long-active zone of crustal weakness, high heat flow, and episodic hydrothermal alteration.

Variations in Carlin Trend Deposits

The relative importance of stratigraphic and structural controls to gold deposits has been recognized by numerous workers on the Carlin trend (Groves, 1996a). Figure A-4 illustrates graphically the relative importance of these types of controls to the range in styles of mineralization. As illustrated, the original Carlin deposit represents the more passively emplaced, stratigraphically controlled end member to a broader spectrum of deposit types. Contrasting structurally controlled mineralization is the dominant style in such deposits as Deep Star, Meikle, and the Deep Sulfide Feeder zone in the Gold Quarry deposit. Since the Carlin discovery, the influence of structure and variations in host lithology has demonstrated that the styles of mineralization on the Carlin trend are as varied as the size and grade of the deposits.
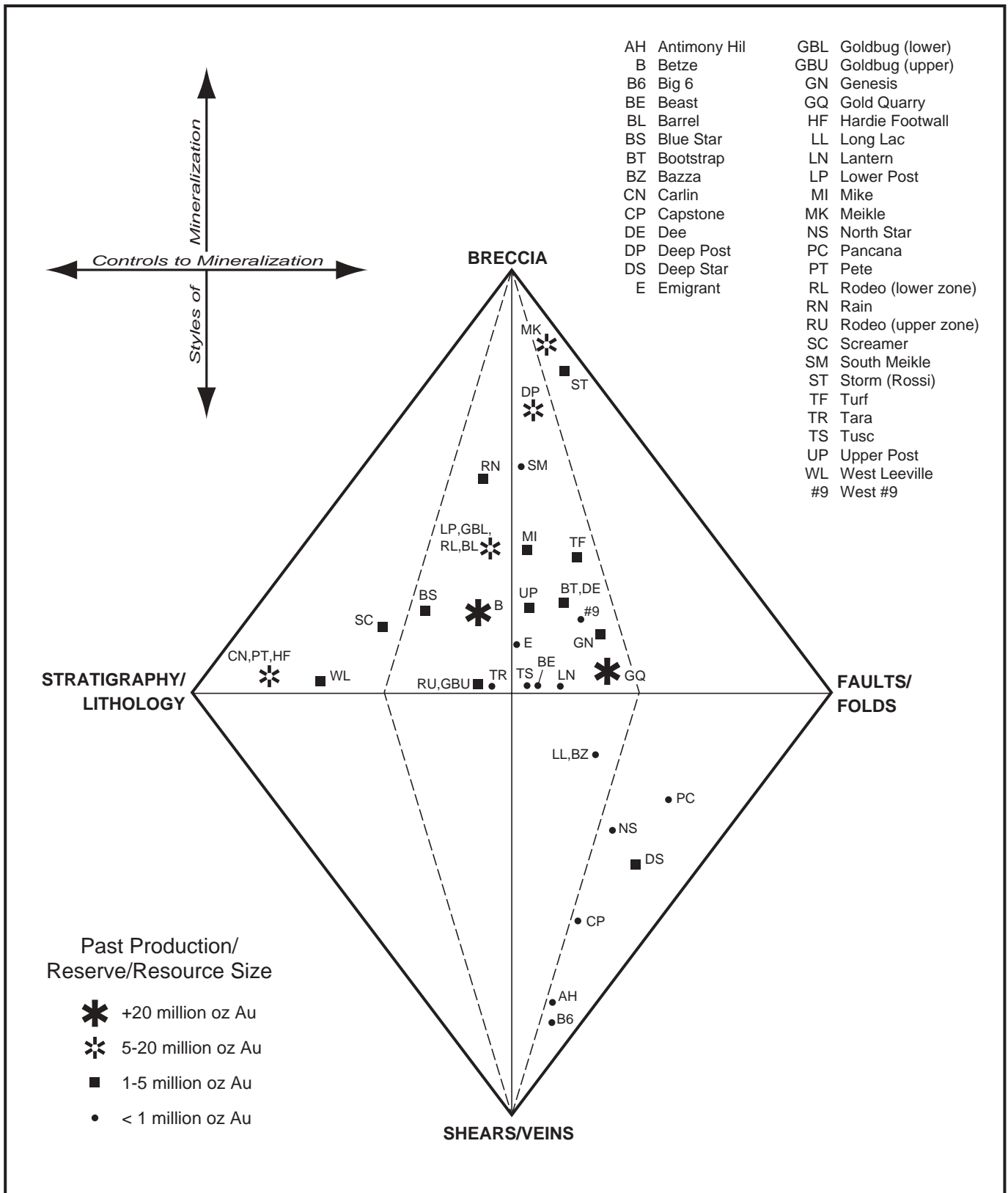
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Figure A-4. Spectrum diagram for various Carlin trend gold deposits.