# SEG NEWSLETTER

SOCIETY OF ECONOMIC GEOLOGISTS

www.segweb.org

OCTOBER 2004 NUMBER 59



*Editor's note: This is the first of a two-part preview of an SEG-sponsored forum to be held in Reno, Nevada, on May 14, 2005. Meeting details are on p. 46.*

# Controversies on the Origin of World-Class Gold Deposits,

## Part I: Carlin-type Gold Deposits in Nevada


***John L. Muntean*** *(SEG 1989 F),** ***Jean Cline*** *(SEG 1983 F),* ***Marcus K. Johnston*** *(SEG 1997),* ***Michael W. Ressel*** *(SEG 1992),* ***Eric Seedorff*** *(SEG 1978 F), and* ***Mark D. Barton*** *(SEG 1979 F)*


## FOREWORD


***John L. Muntean****, Placer Dome Exploration, 240 S. Rock Blvd, Suite 117, Reno, Nevada, USA, 89502*


This article and a future article in the SEG *Newsletter* will serve as previews to an SEG-sponsored forum to examine and discuss the origins of gold deposits in the Carlin and Witwatersrand camps. The forum will be held in Reno, Nevada, on May 14, 2005, in conjunction with Geological Society of Nevada's Symposium 2005 – Window to the World. Both districts have been the focus of major controversies. In this article, three short papers discuss the origin of Carlin-type deposits in north-central Nevada. Over the last few decades, Carlin-type deposits have been seen as shallow hot spring deposits, distal products of porphyry copper deposits, and the uppermost parts of deep mesothermal systems. The first paper, by Jean Cline, provides an introduction to the characteristics of Carlin-type deposits and a framework for discussions of their origin. The second paper, by Marcus Johnston and Michael Ressel, argues for a magmatic origin for the deposits, and specifically that plutons are the source of heat and probably fluids and metals. The third paper, by Eric Seedorff and Mark Barton, discusses amagmatic models for the origin of Carlin-type deposits, as well as pointing out shortcomings in magmatic models. These authors will give talks at the May 2005 forum, which will be followed by panel and open discussions with the aim of identifying what we need to know to better understand and explore for these deposits.


* Corresponding author:
e-mail, John_Muntean@placerdome.com


## INTRODUCTION TO CARLIN-TYPE DEPOSITS


***Jean Cline****, University of Nevada, Las Vegas, Department of Geoscience, 4505 Maryland Parkway, Box 454010, Las Vegas, Nevada, USA, 89154-4010*


Carlin-type deposits currently dominate gold production in the United States and have been largely responsible for the position of the United States as a leading gold producer (Nevada Bureau of Mines and Geology, 2004; Fig. 1). Although similar deposits have been mined since the early 1900s, discovery of the Carlin deposit in 1961 near Carlin, Nevada, and gold exploration that followed it led to recognition of the importance of these deposits to world gold reserves. Since the discovery of the Carlin deposit, over 100 geologically similar "Carlin-type" deposits (Hofstra and Cline, 2000) containing approximately 6,000 tonnes (200 Moz) of gold have been discovered in Nevada. Examples include Betze-Post, Gold Quarry, and Pipeline. Most of these deposits lie within a few linear districts, known as "trends," the Carlin trend being the largest and most famous. Although a number of prospects or deposits around the world have been described as Carlin-type deposits, no trend or district outside Nevada contains similarly large and numerous deposits. Improved understanding of the genesis of these deposits should lead to improved exploration models and a better discovery rate.

The geochemistry, mineralogy, and low-temperature nature of the ore at Carlin, and also at Getchell and Gold Acres—two similar deposits mined prior to the discovery of Carlin—led early workers to conclude that the deposits were a variant of shallow epithermal or hot spring deposits (Joralemon, 1951; Hausen and Kerr, 1968; Roberts et al., 1971; Radtke et al., 1980; Radtke, 1985; Rye, 1985). Other workers, however, concluded that ore characteristics were different enough from typical epithermal systems that the deposits deserved their own classification, and likely formed under different conditions (Wells and Mullens, 1973). Today, after more than 40 years of mining these deposits, workers have developed a detailed geologic picture (Joralemon, 1951; Hausen and Kerr, 1968; Wells et al., 1969; Roberts et al., 1971; Wells and Mullens, 1973; Radtke et al., 1980; Bagby and Berger, 1985; Radtke, 1985; Bakken,

to page 11 · · ·

from 1 Controversies on the Origin of World-Class Gold Deposits (Continued)

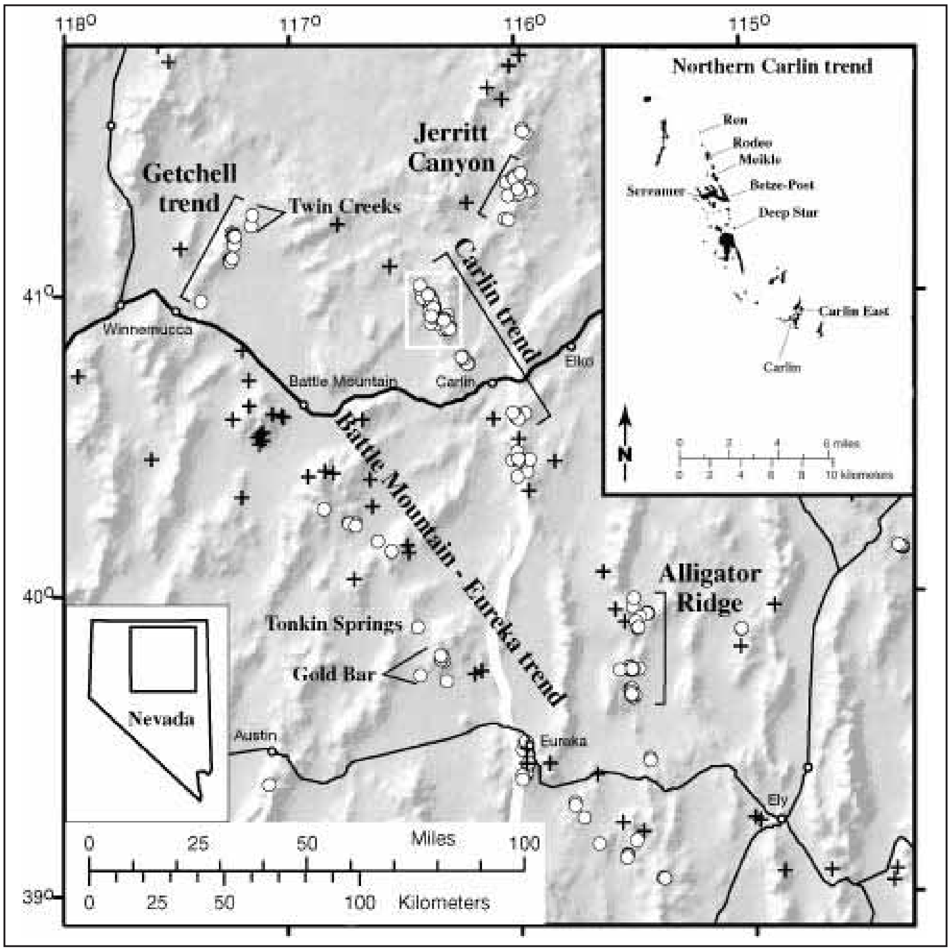


**FIGURE 1.** Digital elevation model of northern Nevada showing locations of major mineral belts and districts. Carlin-type deposits (circles), other significant Au, Ag, Pb, Zn, or Cu deposits (crosses), eastern limit of the Roberts Mountain allochthon, cities (small circles), and highways (black lines). Inset shows the distribution of Carlin-type deposits in the northern Carlin trend. Taken from Hofstra et al. (2003).

1990; Arehart et el., 1993; Hofstra, 1994; Kuehn and Rose, 1992; 1995; Arehart, 1996; Stenger et al., 1998; Hofstra et al., 1999; Hofstra and Cline, 2000; Ressel et al., 2000b; Bettles, 2002; Thompson et al., 2002; Emsbo et al., 2003; Heitt et al., 2003; Kesler et al., 2003). Most of those who work on Carlin-type deposits would agree that these deposits exhibit significant unique characteristics that are distinct from typical epithermal deposits, yet a comprehensive and widely accepted genetic model remains elusive.

Carlin-type ores are distinctive from typical epithermal ores because they form replacement bodies with structural and stratigraphic controls, contain primary gold that is restricted to ionic substitution and submicron-sized grains in arsenian pyrite, and exhibit alteration that is subtle but dominated by decarbonatization of silty calcareous host rocks. Ore mineralogy, textures, fluid inclusion studies, and numerical models (Hofstra et al., 1991; Arehart, 1996; Woitsekhowskaya and Peters, 1998; Stenger et al., 1998; Cline and Hofstra, 2000; Hofstra and Cline, 2000; Kesler et al., 2003) indicate that gold did not precipitate in response to boiling or fluid cooling, as in many epithermal systems, but instead precipitated in response to sulfidation of iron in the host rock or in a second, iron-bearing fluid. Although a few studies have determined pressure and temperature conditions during gold precipitation and sources of ore fluid components, these studies have not converged on a genetic model and, instead, have led to a proliferation of genetic models that can be sorted into three major classifications: (1) epizonal plutons contributed heat and possibly fluids and metals (Sillitoe and Bonham, 1990; Henry and Boden, 1998; Henry and Ressel, 2000); (2) meteoric fluid circulation resulting from crustal extension scavenged and precipitated metals with or without contributions of heat from widespread magmatism (Ilchik and Barton, 1997; Emsbo et al., 2003); and (3) metamorphic fluids from deep or midcrustal levels, possibly with a magmatic contribution, transported and precipitated metals (Seedorff, 1991; Hofstra and Cline, 2000).

The difficulty in sorting out the genesis of Carlin-type deposits is related to the complex geologic history of northern Nevada and specific features of the deposits. For example, minerals that are part of the main ore stage (quartz, pyrite, illite, and locally dickite) are fine grained and volumetrically minor. In addition, northern Nevada has undergone multiple diagenetic and hydrothermal events that produced many of the same minerals as those associated with the Carlin-type deposits, and these events were overprinted by or superimposed on the main ore stage. The geology of many deposits is further complicated by supergene alteration that oxidized the orebodies and mobilized gold, contributing to misinterpretations about deposit genesis during the early years of mining. All these complications make it difficult to analyze mineralized samples and learn about the main ore stage associated with the deposits. Bulk analyses of mineralized samples simply produce a result that is a mixture of several events. Analysis of mineral separates and microanalysis of pyrite, quartz, and fluid inclusions can produce results related to the main ore stage; however, such analyses require painstaking petrography to unravel mineral parageneses and to distinguish gold-related pyrite, quartz, and silicate minerals from pre- or postore minerals.

A major advance in the last several years has been resolution of the age of formation of Nevada's Carlin-type deposits. A late Eocene age has been established by Rb-Sr dating of galkhaite, a late ore stage sulfosalt mineral from the Getchell deposit (39.0 ± 2.1 Ma; Tretbar et al., 2000) and the Rodeo deposit (39.8 ± 0.6 Ma; Arehart et al., 2003) located on the northern Carlin trend. These results demonstrate that

to page 12

• • • from 11 Controversies on the Origin of World-Class Gold Deposits (Continued)

mineralization on the Carlin and Getchell trends is approximately the same age, and available age data from pre- and postore igneous rocks (cf. Hofstra et al., 1999; Arehart et al., 2003) collectively indicate that all deposits formed during a fairly narrow time interval between about 42 and 36 Ma. Establishing this timing has been critically important because the tectonic regime during deposit formation can now be incorporated into a genetic model.

Au-rich porphyry copper (Bingham Canyon, Copper Canyon), skarn (Fortitude, McCoy), and distal-disseminated deposits (Lone Tree, Cove, Hilltop) were also forming in Nevada and Utah during the late Eocene (Doebrich and Theodore, 1996; Theodore, 1998, 2000; Parry et al., 2001). The distal-disseminated deposits share many features with Carlin-type deposits and have led to various genetic interpretations regarding these two deposit types. The U.S. Geological Survey distinguishes distal-disseminated deposits from Carlin-type deposits and defines them as disseminated gold and silver occurring mainly in sedimentary rocks distal to porphyry copper deposits, skarns, and/or polymetallic vein systems (Cox, 1992; Hofstra and Cline, 2000). As pointed out by Hofstra and Cline (2000), the distinction is important in that Carlin-type deposits have much larger gold endowments than distal-disseminated deposits as currently classified. This distinction is challenged in the next paper by Johnston and Ressel, and is the current focal point of controversy surrounding the genesis of Carlin-type deposits.

## CARLIN-TYPE AND DISTAL-DISSEMINATED Au-Ag DEPOSITS: RELATED DISTAL EXPRESSIONS OF EOCENE INTRUSIVE CENTERS IN NORTH-CENTRAL NEVADA

***Marcus K. Johnston***, *Victoria Resources (US) Inc., 605 Cortney Dr., Elko, Nevada, USA, 89801, and*
***Michael W. Ressel***, *Newmont Mining Corporation, P.O. Box 69, Golconda, Nevada, USA, 89414*

### *Introduction*

Sedimentary rock-hosted, disseminated gold deposits are major gold producers, with Nevada production alone exceeding 210 tonnes (7 Moz) in 2000. Most of these deposits in Nevada occur along the Carlin, Battle Mountain-Eureka, and Getchell trends, and include the giant Betze-Post and Gold Quarry mines, as well as Carlin, Cortez, Cove, Deep Star, Genesis, Getchell, Lone Tree, Marigold, Meikle, Pipeline, and Twin Creeks deposits, among others (Fig. 1).

Sedimentary rock-hosted, disseminated gold deposits have been separated into two specific classes: Carlin-type and distal-disseminated Au-Ag deposits. Although distal-disseminated deposits share many physical and geochemical characteristics with Carlin-type deposits, they are differentiated from Carlin-type deposits based on more definitive chemical, spatial, and/or temporal links with porphyry-related deposits. We propose a continuum between Carlin-type and distal-disseminated deposits in the Great Basin, with most or all deposits occurring as peripheral, relatively shallow components of large, complex, magmatic-hydrothermal systems.

### *Background*

Whereas the intrusion-related origin of distal-disseminated deposits is rarely disputed (e.g., Theodore 2000; Hofstra and Cline, 2000; Johnston, 2000, 2003), that of the Carlin-type is highly controversial. Relative to distal-disseminated deposits, Carlin-type deposits generally form at lower temperatures, are commonly not spatially associated with metamorphic aureoles of coeval intrusive stocks, lack strong associations with Ag and base metals, and have isotopic compositions that suggest evolved meteoric fluids and sedimentary rocks as sources for ore-forming components. Northern Nevada also contains late Eocene Au ± Cu porphyry deposits, as pointed out in the first paper. All these deposits fall within a belt of Eocene calc-alkaline magmatism, and most Carlin-type deposits are spatially associated with large Eocene magmatic centers (Christiansen and Yeats, 1992; Henry and Ressel, 2000).

In several districts in Nevada, including Battle Mountain, Bullion-Rain, and McCoy, deposits are zoned along major fault systems from proximal Au ± Cu porphyry and/or skarn deposits, through intermediate polymetallic occurrences, to more distal distal-disseminated deposits. Many workers (e.g., Sillitoe and Bonham, 1990; Seedorff, 1991; Theodore, 1998; Henry and Ressel, 2000; Theodore, 2000; Johnston, 2003) postulate that these deposits represent classically zoned magmatic-hydrothermal systems, based on spatial and temporal associations, but these observations typically lack data to support this inference. Recently, Johnston (2003) used fluid inclusion, metal zoning, and isotopic data to link Eocene magmatism, Au-Ag skarn ore at McCoy, and Carlin-type–distal-disseminated deposits ore at nearby Cove. At McCoy-Cove, Battle Mountain, and the Carlin trend, exposed Eocene intrusions are shallow expressions of much larger intrusions at depth that are thought to have supplied heat and probably metals to Carlin-type and distal-disseminated deposits (Henry and Ressel, 2000; Ressel et al., 2000a, b; Theodore, 2000; Johnston, 2003).

Other studies indicate magmatic ties for some deposits considered to be classic Carlin-type. Deposits in the Carlin trend formed contemporaneously with multiple stages of spatially coincident Eocene magmatism between 42 and 36 Ma (Henry and Ressel, 2000; Ressel et al., 2000a, b). Subvolcanic textures in ore-bearing Eocene dikes support arguments that the deposits formed at shallower depths than those typical of the porphyry-skarn environment of, for example, the Battle Mountain district, where well-defined alteration and metal zoning exist (Theodore, 2000). A direct magmatic tie is indicated at Deep Star, in the northern Carlin trend, where $\delta D$ and $\delta^{18}O$ of ore-stage kaolinite vary from near the magmatic-metamorphic field in the center of the orebody toward exchanged mid-Tertiary meteoric water on its margins (Heitt et al., 2003). The Getchell deposit, for which the Getchell trend is named, is considered by many to be a "classic" Carlin-type deposit, because it shows no apparent relationships with Eocene magmatism other than a temporal link. However, $\delta D$, $\delta^{18}O$, and $^3He/^4He$ from ore-related minerals are consistent with a magmatic (or metamorphic) component in ore fluids (Hofstra and Rye, 1998; Hofstra and Cline, 2000; Cline et al., 2002, 2003).

Growing evidence for magmatic connections indicate that some well-studied

Carlin-type deposits may be better classified as distal-disseminated (Johnston, 2003) and that a distinction between the two types of deposits is not warranted. This inference begs a simple question: if most or all Carlin-type deposits in north-central Nevada are coeval with late Eocene magmatism, a time that also includes the development of large Au-Ag ± Cu skarns with distal-disseminated deposits on their margins, is it not possible, or even probable, that the lower temperature, more Au-rich Carlin-type are even more distal relatives of such systems?

### *Intrusion-related model for Carlin-type deposits*

Figure 2 is a conceptual model that combines ideas from earlier models by Sillitoe and Bonham (1990) and Johnston (2003). Based principally on geothermal conditions and host-rock lithology, there are a number of places within a sedimentary rock-hosted, gold-rich, magmatic-hydrothermal system where porphyry and/or skarn, polymetallic, and Carlin-type and distal-disseminated deposit orebodies can form (Fig. 2C). The model includes Carlin-type and distal-disseminated deposits as distal and generally shallow

to page 14 · · ·

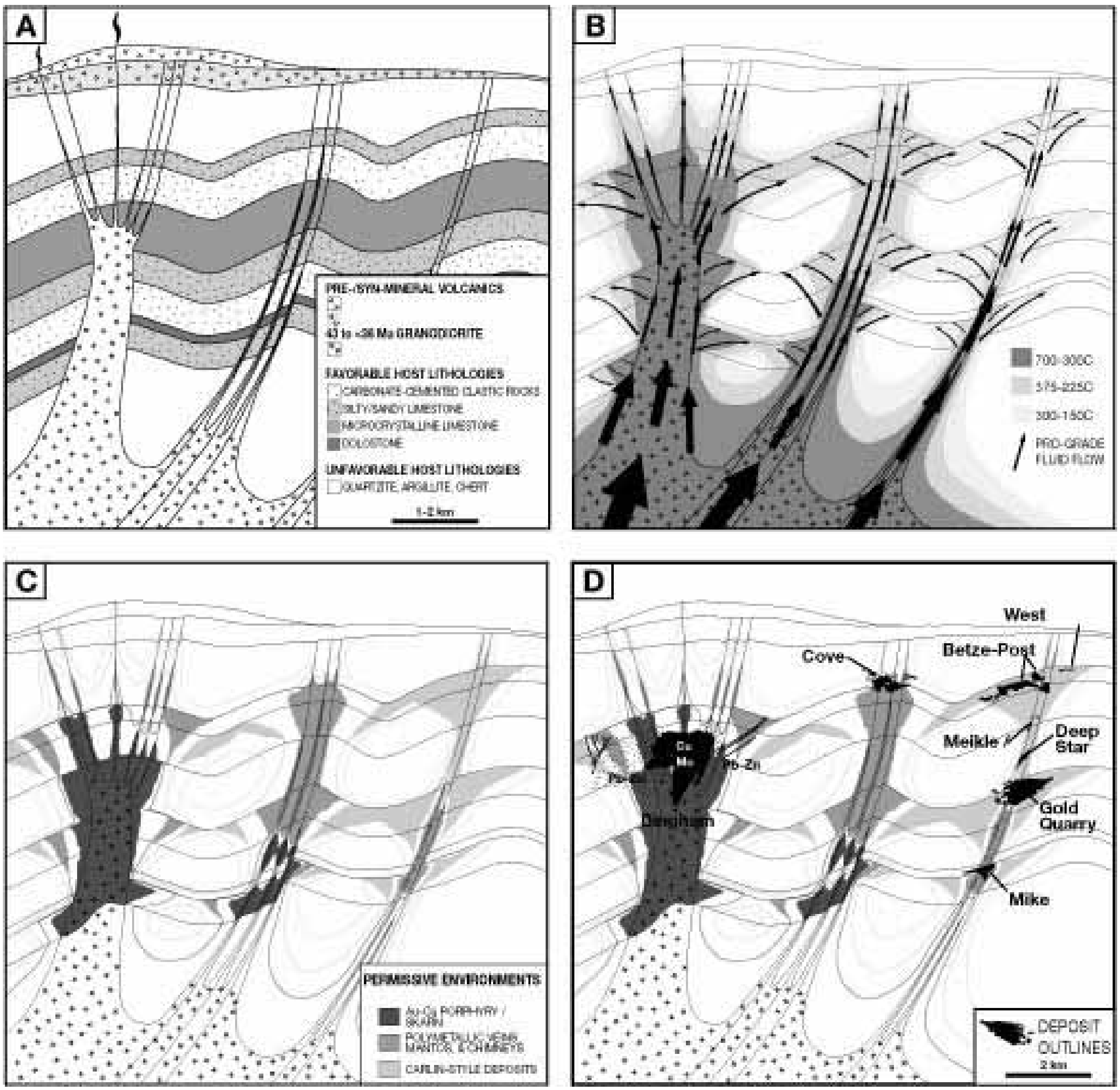


**FIGURE 2.** Hypothetical zoning patterns related to an idealized Eocene magmatic-hydrothermal system in the Great Basin physiographic province, United States. A. Geology, emphasizing more favorable units based on higher permeability and/or reactivity. B. Temperature and prograde flow regime, with fluids derived from a large magma chamber at depth. C. Possible depositional environments for various deposit types, based on temperature and protolith. D. Examples of Eocene gold deposit types (deposit shapes modified from Babcock et al., 1997; Bettles, 2002; Clode et al., 2002; Harlan et al., 2002; Jackson et al., 2002; Norby and Orobona, 2002; Johnston, 2003). Scale bar in A applies to all cross sections; the scale bar in D applies only to the deposit outlines.

· · · from 13 Controversies on the Origin of World-Class Gold Deposits (Continued)

(<4 km) components of the system. These depths are supported by a recent study of the Carlin trend, based on fission-track data (Hickey et al., 2003).

Most Carlin-type and distal-disseminated deposits that lie within the major trends are not direct products of shallow and relatively small (1–3 km$^2$) porphyry stocks responsible for Au skarns of the same age, and do not require the presence of such stocks. Instead, they are related to much larger (10–100 km$^2$), underlying intrusions (>5 km depth) of intermediate to silicic composition and reduced character. These intrusions, of batholithic scale under the Carlin trend and Battle Mountain (Grauch, 1996; Rodriguez, 1998; Henry and Ressel, 2000), for example, are argued to have supplied heat and some fluids and metals to broad, overlying hydrothermal systems, and magma to many high-level porphyries. Eocene magmatism in and near the major trends was dominantly intrusive in character; volcanism was relatively minor or possibly nonexistent in some areas, and may have followed main-stage mineralization (Henry and Boden, 1998; Henry and Ressel, 2000; Ressel et al., 2000a).

Magmatism and hydrothermal circulation were focused along deep-seated faults, which influenced the distribution of deposits along trends (Grauch et al., 2003). Deposits and clusters of deposits generally relate to intersections between the deep-seated faults and other structures, principally other high-angle faults and/or anticlines (cf. Hofstra and Cline, 2000). Important deposit-scale mechanisms leading to Au deposition in Carlin-type and distal-disseminated deposits are generally well established (e.g., Hofstra and Cline, 2000), and include the following: (1) fluid–wall-rock reaction, causing decarbonatization, silicification, and dolomitization of carbonate rocks and argillization of igneous rocks; and (2) sulfidation of reactive iron. Because these mechanisms are not sensitive to pressure, depth is not important. Ore could have precipitated over a great vertical (and horizontal) range without any apparent strong zonations, as observed in many of the Carlin-type deposits in the Carlin and Getchell trends. On the margins of large magmatic-hydrothermal systems, where we propose Carlin-type deposits form, remobilization of at least some wall-rock components during mineralization cannot be ruled out, and may be the norm. Circulation of meteoric, connate, or other fluids and the associated remobilization of wall-rock components may account for nonmagmatic signatures of mineralizing fluids and variable isotopic signatures for mineralizing components observed in many Carlin-type deposits.

Areas for future research should include the relative timing of extension and ore formation, palinspastic reconstructions of mineralized districts, modeling of Eocene heat flow as a function of large intrusions and/or crustal extension, and isotopic constraints of ore-related minerals in the highest grade Carlin-type deposits. As indicated by the magmatic (or metamorphic) ties for Getchell and Deep Star, high-grade, structurally controlled Carlin-type deposits may be less influenced by shallow meteoric fluids and should be investigated to better characterize deeper source fluids.

## ENIGMATIC ORIGIN OF CARLIN-TYPE DEPOSITS: AN AMAGMATIC SOLUTION?

***Eric Seedorff*** *(SEG 1978 F) and*
***Mark D. Barton*** *(SEG 1979 F), Center for Mineral Resources, Department of Geosciences, 1040 East Fourth Street, University of Arizona, Tucson, Arizona 85721-0077 USA*

Conceptual models for Carlin-type deposits have narrowed to three broad classes, two of which are amagmatic: (1) surface-derived and/or basinal; (2) metamorphic (orogenic); and (3) magmatic (Fig. 3, top). All potentially produce jasperoid in calcareous rock

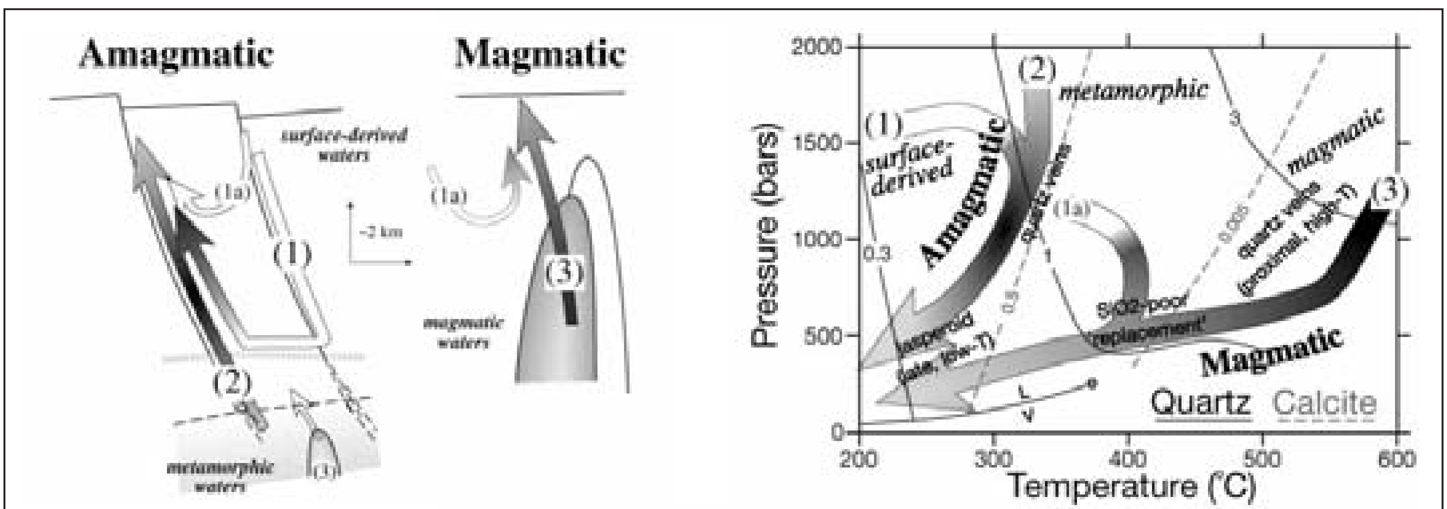


**FIGURE 3.** Models for Carlin-type gold deposits. Left: Sketches showing conceptual models. Arrows show movement of fluid; darker shading within arrows shows where fluids deposit quartz. Model 1 shows surface-derived waters descending down normal faults to the brittle-ductile transition zone then returning to surface to form gold deposits. Model 2 shows metamorphic waters rising along faults. Small arrow labeled 3 shows possible subordinate magmatic inputs to either model. Model 3 shows magmatic-hydrothermal system related to multiple intrusions. All models have minor inputs of unevolved meteoric water (1a). Right: Solubilities of calcite and quartz (grams/kg $H_2O$) showing contrasting paths for siliceous replacements for models, all ending in formation of jasperoid (from Barton et al., 1997). Solubilities are for pure water and are calculated from the data in Johnson et al. (1992).

**TABLE 1.** Predictions from Models for Carlin-Type Gold Deposits

| | Amagmatic | | Magmatic |
|---|---|---|---|
| **Characteristic** | **1. Surface-derived and/or basinal** | **2. Metamorphic (orogenic)** | **3. Magmatic** |
| Alteration and zoning | Regional scale; weak zonation | Regional scale; weak zonation | A few km across; zoned around intrusions and higher temperature alteration |
| Role of magmatism | Nonessential | Nonessential | Essential; plutons provide metals and fluid |
| Primary source of materials | Scavenged from upper crust, primarily clastic rocks of miogeocline | Various, depending on site of metamorphism, including base of miogeocline | Mineralizing pluton; should correlate with magma composition |
| Primary source of heat | Thermal energy extracted from upper crust by extension-driven increases in permeability | Mantle derived/ underplated magmas/crustal thickening | Local magmas |
| Temperatures of quartz deposition | Constrained by temperature of brittle-ductile transition: <350°C | Could be >400°C | Nonspecific |

types at low temperatures by following different geochemical pathways (Fig. 3, bottom). Each hypothesis, however, makes a different set of predictions; the types of systems develop at fundamentally different spatial scales, and the models imply different exploration strategies (Fig. 4).

We will not advocate a particular model. Our purpose, as it has been in the past (Barton et al., 1997), is to stimulate discussion and further testing of hypotheses to avert a rush to adopt any particular origin.

### Geologic setting

Hofstra and Cline (2000), Thompson et al. (2002), and Hofstra et al. (2003) have reviewed the key features of Carlin-type deposits, including their ages. We focus here on northeastern Nevada, in the vicinity of Carlin itself. The deposits formed between 42 and 36 Ma, following a long period of contraction and crustal thickening of the miogeocline. The ages of deposits coincide with the initiation of extension in this region, but although the region contains domains of extreme extension, the gold deposits are not centered on those domains. The region also has been the site of lacustrine deposition before, during, and after formation of the ore deposits. The ore-forming fluids associated with the deposits are mildly saline, slightly acidic, and fairly reduced.

### Surface-derived and/or basinal systems

In surface-derived or basinal models, surface, ground, and connate waters are introduced into the developing hydrothermal system via faults, fractures, and pores. Flow begins in response to ambient or magma-enhanced thermal gradients, topographic effects, or burial, and fluids flow up temperature in the early parts of their paths. In the complementary part of the flow path, perhaps triggered by tectonic events, fluids migrate to areas of lower pressures along structures and strata, where they interact with other fluids and rocks, cool, and can deposit metals by any of a variety of mechanisms. The types of metals precipitated depend on factors such as the compositions of the surficial fluids (dilute, saline, concentrated brines), the compositions of rocks along the heating path and in the reservoir, the temperature of the fluids upon release, and the nature of interactions near the site of deposition (Ilchik and Barton, 1997). The Viburnum trend, a Mississippi Valley-type Pb-Zn district, is shown to illustrate the geometry and scale of one such type of regional hydrothermal system (Fig. 4).

In the setting of Carlin-type deposits, extension allows for and crustal heat or changing topography drives the deep circulation of surface-derived fluids through clastic rocks in the lower parts of the miogeoclinal section that are reduced and have high background levels of the metals found in Carlin-type systems (Nesbitt, 1988; Ilchik and Barton, 1997). This model predicts that carbonate would be leached and quartz deposited mostly in the shallow crust near the deposit, that ore fluids would be relatively dilute, and that the hydrothermal systems would be regional-scale features exhibiting weak zonation. Regionally, deposits would occur where areas of rapid extension and thus large increases in permeability overlap with favorable source rocks at depth. A challenge is to explain the localization of deposits in the structural domains that were not highly extended at the surface.

### Metamorphic (orogenic) systems

In this model, Carlin-type deposits are derived from metamorphic fluids or deep crustal and mantle sources, released by earthquakes on regional fault systems. The deposits might be regarded as updip extensions of orogenic gold systems (e.g., Groves et al., 1998). Alternatively, the initiation of extension might tap preexisting fluid reservoirs in the clastic part of the miogeocline (Seedorff, 1991). Figure 4 shows the central part of the Mother Lode gold belt, illustrating the geometry and scale of this type of regional hydrothermal system.

This model has similarities to the previous one, but differs in that the temperature of quartz vein deposition might be higher such that Carlin-type deposits could be rooted in large quartz veins. A challenge is to have metamorphic waters available in the Eocene, when Carlin-type deposits formed, if the peak of metamorphism was in the Late Cretaceous or early Tertiary during the period of contraction and crustal thickening. Alternatively, there could also have been a later metamorphic event in the Eocene if there were sufficiently large volumes of underplated Eocene magmas.

### Magmatic

In this model, the deposits are related to intrusion-centered, magmatic-hydrothermal systems. They could be related to

to page 16 · · ·

· · · from 15 Controversies on the Origin of World-Class Gold Deposits (Continued)

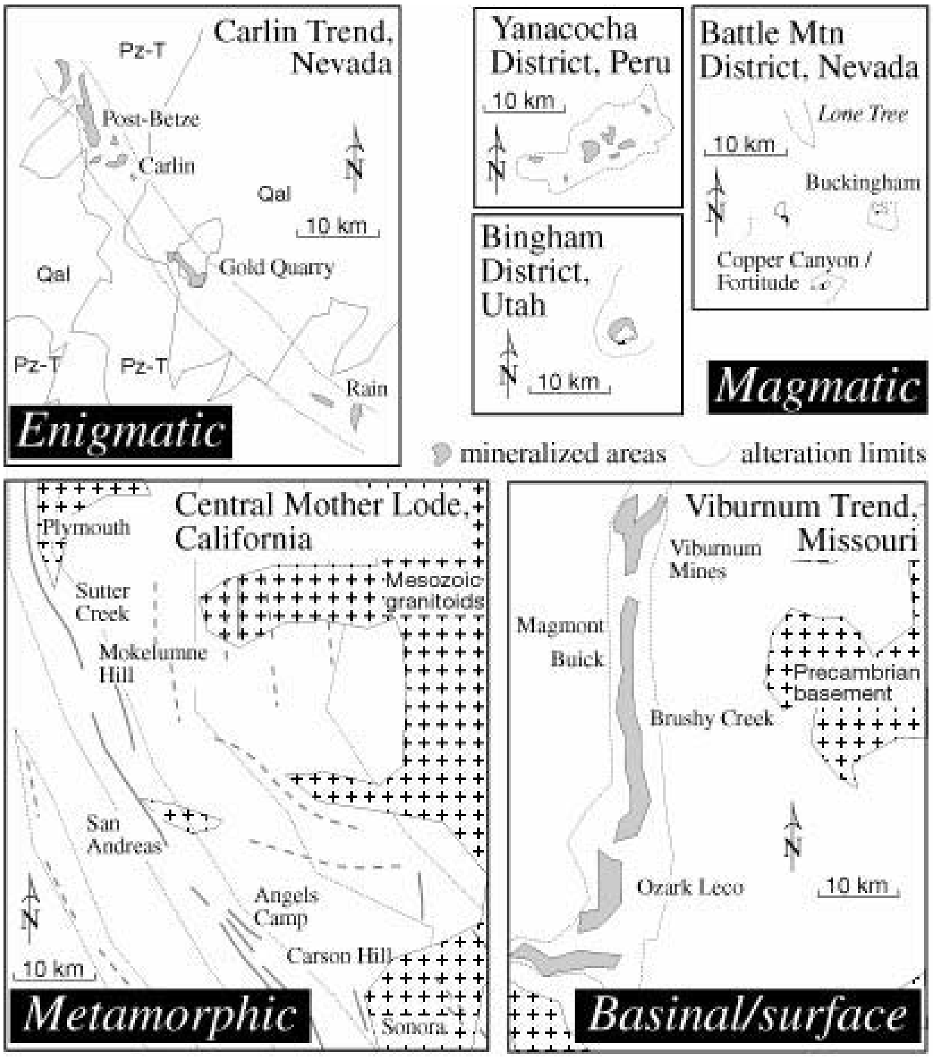


**FIGURE 4.** Plan maps comparing the surface expression of alteration and ore in the Carlin trend to examples of districts that correspond to the magmatic, metamorphic, and basinal- and surface models discussed in the text, all drawn at the same scale.

porphyry deposits (Alvarez and Noble, 1988; Sillitoe and Bonham, 1990) or some other type of magmatic system (Henry and Ressel, 2000). Figure 4 shows three examples, two of which are giants in their classes: Bingham, which is a gold-rich porphyry copper deposit, and Yanacocha, which is a high-sulfidation gold deposit with associated porphyry-style mineralization. The third example is from the nearby Battle Mountain district, which is a composite of multiple systems of various ages. In surface area, the Carlin trend, sensu stricto, dwarfs them all.

In addition to the seeming mismatch in scales, challenges include finding a zonation toward higher temperature alteration, such as cogenetic skarn or hydrothermal feldspar and biotite, and identifying compositions of mineralizing intrusions.

### *Discussion*

Plutons of various ages abound in Nevada, regardless of whether they played any significant role in the origin of Carlin-type deposits, just as plutons occur near Viburnum and the Mother Lode (Fig. 4). We have always acknowledged that distal-disseminated deposits are magmatic, but their alteration patterns are not of regional extent, nor are the amounts of contained gold comparable to the principal trends of Carlin-type deposits; rather, the largest gold inventories are proximal to the intrusions (Seedorff, 1991; Barton et al., 1997). Eocene porphyry systems are present nearby, as at Battle Mountain; indeed, hybrid systems with magmatic and regional fluid inputs (Lone Tree?) are possible (Fig. 4). Neither distal-disseminated deposits nor superposition of unrelated deposits, however, should be allowed to cloud the origin of regional-scale systems such as deposits of the Carlin trend.

The powerful allure of magmatic processes once prevented earlier generations from recognizing the importance of nonmagmatic fluid circulation and syngenetic depositional processes in volcanogenic massive sulfide deposits (Stanton, 1991). That shift in paradigm ushered in a new wave of scientific and exploration breakthroughs. With a shift in paradigm, comparable breakthroughs may be possible for Carlin-type deposits.

## ACKNOWLEDGMENTS

All of the above authors give thanks to the many geologists who have worked on these deposits over the years and the many mining companies who have supported research, funded studies, given tours, and allowed data/results to be disseminated. Reviews by Odie Christensen, Stephen Kesler, and Jeremy Richards are greatly appreciated.

### REFERENCES

Alvarez, A.A., and Noble, D.C., 1988, Sedimentary rock-hosted disseminated precious metal mineralization at Purísima Concepción, Yauricocha district, central Peru: Economic Geology, v. 83, p. 1368–1378.

Arehart, G.B., 1996, Characteristic and origin of sediment-hosted disseminated gold deposits: A review: Ore Geology Reviews, v. 11, p. 383–403.

Arehart, G.B., Eldridge, C.A., Chryssoulis, S.L., and Kesler, S.E., 1993, Ion microprobe determination of sulfur isotope variations in iron sulfides from the Post/Betze sediment-hosted disseminated gold deposit, Nevada, U.S.A.: Geochimica et Cosmochimica Acta, v. 57, p. 1505–1519.

Arehart, G.B., Chakurian, A.M., Tretbar, D.R., Christensen, J.N., McInnes, B.A., and Donelick, R.A., 2003, Evaluation of radioisotope dating of Carlin-type deposits in the Great Basin, western North America, and implications for deposit genesis: Economic Geology, v. 98, p. 235–248.

Bagby, W.C. and Berger, B.R., 1985, Geologic characteristics of sediment-hosted, disseminated precious-metal deposits in the western United States: Reviews in Economic Geology, v. 2, p. 169–202.

Babcock, R.C., Jr. Ballantyne, G.H., and Phillips, C.H., 1997, Summary of the geology of the Bingham District, Utah: Society of Economic Geologists Guidebook Series, v. 29, p. 113–132.
Bakken, B.M., 1990, Gold mineralization, wall rock alteration, and the geochemical evolution of the hydrothermal system in the main orebody, Carlin mine, Nevada: Unpublished Ph.D. dissertation, California, Stanford University, 236 p.
Barton, M.D., Seedorff, E., Ilchik, R.P., and Ghidotti, G., 1997, Contrasting siliceous replacement mineralization, east-central Nevada [extended abs.]: Society of Economic Geologists Guidebook Series, v. 28, p. 131–134.
Bettles, K., 2002, Exploration and geology, 1962 to 2002, at the Goldstrike property, Carlin trend, Nevada: Society of Economic Geologists Special Publication 9, p. 275–298.
Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region: Conterminous U.S., *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran orogen: Conterminous U.S.: Geological Society of America, The Geology of North America, v. G-3, p. 261–406.
Cline, J.S., and Hofstra, A.H., 2000, Ore fluid evolution at the Getchell Carlin-type gold deposit, Nevada, USA: European Journal of Mineralogy, v. 12. p. 195–212.
Cline, J.S., Stuart, F.M., Hofstra, A.H., Tretbar, D.R., Riciputi, L., and Premo, W., 2002, He, Nd, and stable isotope constraints on Carlin-type ore fluid components, Getchell, NV, USA [abs.]: Geological Society of America, Abstracts with Programs, v. 34, no. 6, p. 141.
Cline, J.S., Shields, D., Riciputi, L., Fayek, M., Copp, T.L., Muntean, J., and Hofstra, A.H., 2003, Trace element and isotope microanalyses support a deep ore fluid source at the Getchell Carlin-type gold deposit, northern Nevada [abs.]: Geological Society of America, Abstracts with Programs, v. 35, no. 6, p. 358.
Clode, C.H., Grusing, S.R., Johnston, I.M., and Heitt, D.G., 2002, Geology of the Deep Star gold deposit: Gold deposits of the Carlin trend: Nevada Bureau of Mines and Geology, Bulletin 111, p. 76–90.
Cox, D.P., 1992, Descriptive model of distal disseminated Au-Ag: Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, 168 p.
Doebrich, J.L., and Theodore, T.G., 1996, Geologic history of the Battle Mountain mining district, Nevada, and regional controls on the distribution of mineral systems: Geology and Ore Deposits of the American Cordillera Symposium, Geological Society of Nevada, Reno-Sparks, April 1995, Proceedings, p. 453–483.
Emsbo, P., Hofstra, A.H., Lauha, E.A., Griffin, G.L., and Hutchinson, R.W., 2003, Origin of high-grade gold ore, source of ore fluid components, and genesis of the Meikle and neighboring Carlin-type deposits, northern Carlin trend, Nevada: Economic Geology, v. 98, p. 1069–1105.
Grauch, V.J.S., 1996, Magnetically interpreted, granitoid plutonic bodies in Nevada: An analysis of Nevada's metal-bearing mineral resources: Nevada Bureau of Mines and Geology, Open-File Report 96-2, p. 7-1–7-16.
Grauch, V.J.S., Rodriguez, B.D., Wooden, J.L., 2003, Geophysical and isotopic constraints on crustal structure related to mineral trends in north-central Nevada and implications for tectonic history: Economic Geology, v. 98, pp. 269–286.
Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., and Robert, F., 1998, Orogenic gold deposits: A proposed classification in the context of their crustal contribution and relationship to other gold deposit types: Ore Geology Reviews, v. 13, p. 7–27.
Harlan, J.B., Harris, D.A., Mallette, P.M., Norby, J.W., Rota, J.C., and Sagar, J.J., 2002, Geology and mineralization of the Maggie Creek District: Gold deposits of the Carlin trend: Nevada Bureau of Mines and Geology, Bulletin 111, p. 115–142.
Hausen, D.M., and Kerr, P.F., 1968, Fine gold occurrence at Carlin, Nevada, *in* Ridge, J.D., ed., Ore Deposits of the United States, 1933-1967: New York, AIME, v. 1, p. 908–940.
Heitt, D.G., Dunbar, W.W., Thompson, T.B., and Jackson, R.G., 2003, Geology and geochemistry of the Deep Star gold deposit, Carlin trend, Nevada: Economic Geology, v. 98, p. 1107–1136.
Henry, C.D., and Boden, D.R., 1998, Eocene magmatism: The heat source for Carlin-type gold deposits of northern Nevada: Geology, v. 26, p. 1067–1070.
Henry, C.D., and Ressel, M.W., 2000, Eocene magmatism—the smoking gun for Carlin-type gold deposits: Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium, Reno, May 15–18, 2000, Proceedings, p. 365–388.
Hickey, K.A., Donelick, R.A., Tosdal, R.M., and McInnes, B.I.A., 2003, Restoration of the Eocene landscape in the Carlin-Jerritt Canyon mining district: Constraining depth of mineralisation for Carlin-type Au-deposits using low-temperature apatite thermochronology [abs.]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 358.
Hofstra, A.H., 1994, Geology and genesis of the Carlin-type gold deposits in the Jerritt Canyon district: Nevada, Unpublished Ph.D. dissertation, University of Colorado, 719 p.
Hofstra, A.H., and Cline, J.S., 2000, Characteristics and models for Carlin-type gold deposits: Reviews in Economic Geology, v. 13, p. 163–220.
Hofstra, A.H., and Rye, R.O., 1998, $\delta D$ and $\delta^{18}O$ data from Carlin-type gold deposits: Implications for genetic models: U.S. Geological Survey, Open-File Report 98-0338-B, p. 202–210.
Hofstra, A.H., Leventhal, J.S., and Northrop, G.P., 1991, Genesis of sediment-hosted disseminated-gold deposits by fluid mixing and sulfidiation: Chemical-reaction-path modeling of ore-depositional processes documented in the Jerritt Canyon district, Nevada: Geology, v. 19, p. 36–40.
Hofstra, A.H., Snee, L.W., Rye, R.O., Folger, H.W., Phinisey, J.D., Loranger, R.J., Dahl, A.R., Naeser, C.W., Stein, H.J., and Lewchuk, M., 1999, Age constraints on Jerritt Canyon and other Carlin-type gold deposits in the western United States—relationship to mid-Tertiary extension and magmatism: Economic Geology, v. 94, p. 769–802.
Hofstra, A.H., John, D.A., and Theodore, T.G., eds., 2003, A special issue devoted to gold deposits in northern Nevada: Part. 2. Carlin-type deposits: Economic Geology, v. 98, no. 6.
Ilchik, R.P., and Barton, M.D., 1997, An amagmatic origin of Carlin-type gold deposits: Economic Geology, v. 92, p. 269–288.
Jackson, M., Lane, M., and Leach, B., 2002, Geology of the West Leeville deposit: Gold deposits of the Carlin trend: Nevada Bureau of Mines and Geology, Bulletin 111, p. 106–114.
Johnson, J.W., Olkers, E.H., and Helgeson, H.C., 1992, SUPCRT92: A software package for calculating the standard molal thermodynamic properties of minerals, gases, aqueous species and reactions from 1 to 5000 bars and 0° to 1000°C: Laboratory of Theoretical Geochemistry, University of California, Berkeley.
Johnston, M.K., 2000, Hypogene alteration and ore characteristics at the Cove gold-silver deposit, Lander County, Nevada: Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium, Reno, May 15–18, 2000, Proceedings, p. 621–641.
——2003, Geology of the Cove mine, Lander County, Nevada, and a genetic model for the McCoy-Cove magmatic-hydrothermal system: Unpublished Ph.D. dissertation, University of Nevada, Reno, 353 p.
Joralemon, P., 1951, The occurrence of gold at the Getchell mine, Nevada: Economic Geology, v. 46, p. 267–310.
Kesler, S. E., Fortuna, J., Ye, Z., Alt, J. C., Core, D. P., Zohar, P., Borhauer, J., and Chryssoulis, S.L., 2003, Evaluation of the role of sulfidation in deposition of gold, Screamer section of the Betze-Post Carlin-type deposit, Nevada: Economic Geology, v. 98, p. 1137–1157.
Kuehn, C.A., and Rose, A.W., 1992, Geology and geochemistry of wall-rock alteration at the Carlin gold deposit, Nevada: Economic Geology, v. 87, p. 1697–1721.
——1995, Carlin gold deposits, Nevada: Origin in a deep zone of mixing between normally pressured and overpressured fluids: Economic Geology, v. 90, p. 17–36.

to page 18 • • •

· · · from 17 Controversies on the Origin of World-Class Gold Deposits (Continued)


Nesbitt, B.E., 1988, Gold deposit continuum: A genetic model for lode Au mineralization in the continental crust: Geology, v. 16, p. 1044–1048.

Nevada Bureau of Mines and Geology, 2004, The Nevada Mineral Industry 2003, Special Publication MI-2003, 66 p.

Norby, J.W., and Orobona, M.J.T., 2002, Geology and mineral systems of the Mike Deposit: Gold deposits of the Carlin trend: Nevada Bureau of Mines and Geology, Bulletin 111, p. 143–167.

Parry, W.T., Wilson, P.N., Moser, D., and Heizler, M.T., 2001, U-Pb dating of zircon and $^{40}Ar/^{39}Ar$ dating of biotite at Bingham, Utah: Economic Geology, v. 96, p. 1671–1683.

Radtke, A.S, 1985, Geology of the Carlin gold deposit, Nevada: U.S. Geological Survey Professional Paper 1267, 127 p.

Radtke, A.S., Rye, R.O., and Dickson, F.W., 1980, Geology and stable isotopes studies of the Carlin gold deposit, Nevada: Economic Geology, v. 75, p. 641–673.

Ressel, M.W., Noble, D.C., Henry, C.D., and Trudel, W.S., 2000a, Dike-hosted ores of the Beast deposit and the importance of Eocene magmatism in gold mineralization of the Carlin trend, Nevada: Economic Geology, v. 95, p. 1417–1444.

Ressel, M.W., Noble, D.C., Volk, J.A., Lamb, J.B., Park, D.E., Conrad, J.E., Heizler, M.T., and Mortensen, J.K., 2000b, Precious-metal mineralization in Eocene dikes at Griffin and Meikle: Bearing on the age and origin of gold deposits of the Carlin trend, Nevada: Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium, Reno, May 15–18, 2000, Proceedings, p. 79–101.

Roberts, R.J., Radtke, A.S., Coats, R.R., Silberman, M.L. and McKee, E.H., 1971, Gold-bearing deposits in north-central Nevada and southwestern Idaho, with a section on periods of plutonism in north-central Nevada: Economic Geology, v. 66, p. 14–33.

Rodriguez, B.D., 1998, Regional crustal structure beneath the Carlin trend, Nevada based on deep electrical geophysical measurements: Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report 98-338, p. 15–19.

Rye, R. O., 1985, A model for the formation of carbonate-hosted disseminated gold deposits based on geologic, fluid inclusion, geochemical, and stable isotope studies of the Carlin and Cortez deposits, Nevada: Geologic characteristics of sediment- and volcanic-hosted disseminated gold deposits—search for an occurrence model: U.S. Geological Survey Bulletin 1646, p. 35–42.

Seedorff, E., 1991, Magmatism, extension, and ore deposits of Eocene to Holocene age in the Great Basin—Mutual effects and preliminary proposed genetic relationships: Geology and ore deposits of the Great Basin: Geological Society of Nevada, Symposium, Reno-Sparks, April 1990, Proceedings, v. 1, p. 133–178.

Sillitoe, R.H., and Bonham, H. F., Jr., 1990, Sediment-hosted gold deposits: Distal products of magmatic-hydrothermal systems: Geology, v. 18, p. 157–161.

Stanton, R.L., 1991, Understanding volcanic massive sulfides—Past, present, and future: Economic Geology Monograph 8, p. 82–95.

Stenger, D.P., Kesler, S.E., Peltonen, D.R., and Tapper, C.J., 1998, Deposition of gold in Carlin-type deposits: The role of sulfidation and decarbonation at Twin Creeks, Nevada, Economic Geology, v. 93, p. 201–215.

Theodore, T.G., 1998, Large distal-disseminated precious-metal deposits, Battle Mountain mining district, Nevada: U.S. Geological Survey Open-File Report 98-338, p. 253–258.

——2000, Geology of pluton-related gold mineralization at Battle Mountain, Nevada: Tucson, Arizona, Center for Mineral Resources, Monographs in Mineral Resource Science 2, 271 p.

Thompson, T.B., Teal, L., and Meeuwig, R.O., 2002, Gold deposits of the Carlin trend: Nevada Bureau of Mines and Geology Bulletin 111, 204 p.

Tretbar, D.R., Arehart, G.B., Christensen, J.N., 2000, Dating gold deposition in a Carlin-type gold deposit using Rb/Sr methods on the mineral galkhaite: Geology, v. 28, p. 947–950.

Wells, J.D., and Mullens, T.E., 1973, Gold-bearing arsenian pyrite determined by microprobe analysis, Cortez and Carlin gold mines, Nevada: Economic Geology, v. 68, p. 187–201.

Wells, J.D., Stoiser, L.R., and Elliott, J.E., 1969, Geology and geochemistry of the Cortez gold deposit, Nevada, Economic Geology, v. 64, p. 526–537.

Woitsekhowskaya, M.B., and Peters S.G., 1998, Geochemical modeling of alteration and gold deposition in the Betze deposit, Eureka County, Nevada: Contributions to the gold metallogeny of northern Nevada: U. S. Geological Survey Open-File Report 98-338, p. 211–222.