DIVERSITY OF CARLIN-STYLE GOLD DEPOSITS

Editor
John L. Muntean

SOCIETY OF ECONOMIC GEOLOGISTS, INC.
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SOCIETY OF ECONOMIC GEOLOGISTS, INC.
Reviews in Economic Geology is a series publication of the Society of Economic Geologists designed to accompany the Society’s Short Course series. Like the Short Courses, each volume provides comprehensive updates on various applied and academic topics for practicing economic geologists and geochemists in exploration, development, research, and teaching. Volumes are produced in conjunction with each new Short Course, first serving as a textbook for that course and subsequently made available to SEG members and others at a modest cost.

On the cover: Map showing locations of Carlin-style gold deposits discussed in this volume: Great Basin, Nevada; Dian-Qian-Gui “Golden Triangle,” SW China; Nadaleen trend, Yukon, Canada; Bau district, Sarawak, Malaysia; Agdarreh and Zarshouran deposits, NW Iran; and Allchar deposit, Republic of Macedonia. Inset shows possible interrelationships between various sources of ore fluid and types of Carlin-style deposits, described in the introduction by Muntean in this volume.
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The vast majority of research on Carlin-type gold deposits has been on the large deposits in Nevada, specifically deposits in the Carlin trend and in the Getchell, Cortez, and Jerritt Canyon areas. That research has demonstrated those deposits share many common features despite differences in their local geologic settings. In comparison, less research has been done on other deposits in Nevada and surrounding areas of the Great Basin, as well as in other countries. This volume stemmed from the realization that in order to advance our understanding of Carlin-type deposits, the smaller, slightly different deposits needed more research. With that motivation, John Muntean and Moira Smith, with the help of Al Hofstra, put together a forum sponsored by the Society of Economic Geologists highlighting the diversity of Carlin-style gold deposits in the world. The forum, held in Reno, Nevada, in May 2015, was part of a Geological Society of Nevada Symposium. Most of the first authors of the papers in this volume gave presentations at that forum. An outcome of the forum was a growing realization that the large deposits in Nevada represent end members and the other, similar deposits represent different end members with likely continua between these end members. As stressed in the Introduction, the more we study these hybrid deposits, the more we will understand the processes that control these continua, with the ultimate goal of truly understanding the end member composed of the giant deposits in Nevada.

John L. Muntean
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Matthew Fithian graduated from the University of Colorado at Boulder with a B.A. degree in geological sciences and from Colorado School of Mines with an M.S. degree in geology. In 2014 he joined the exploration group at the Marigold mine, where he has continued to contribute toward the understanding of disseminated gold deposits in the northern Battle Mountain mining district. Matthew has served as vice president (2015–2017) and president (2017–2018) of the Geological Society of Nevada Winnemucca Chapter.

Craig Gibson received his B.S. degree (1984) in earth sciences from the University of Arizona and M.S. (1987) and Ph.D. (1992) degrees in economic geology and geochemistry from the Mackay School of Mines, University of Nevada, Reno. He was a research associate at Mackay from 1992 to 1994, working on coupled field and laboratory investigations of hydrothermal systems in North and South America. He has been active in the exploration industry since 1994, mainly in Mexico. He has been associated with private and public exploration companies involved in exploration for a wide variety of deposit types, including epithermal precious metal deposits, shear-hosted gold deposits, sedimentary rock-hosted gold deposits, porphyry copper systems, base metal skarns, carbonate replacement deposits, and volcanogenic massive sulfide deposits in the U.S., Mexico, Peru, Argentina, Chile, and Bolivia. He cofounded Proseccion y Desarrollo Minero del Norte, S.A. de C.V. (ProDeMin), a consulting firm providing a broad spectrum of exploration related services to the mining industry and based in Guadalajara, Mexico, in 2009. Craig is also a director of Garibaldi Resources Corp., a Vancouver-based junior exploration company, and is a Certified Professional Geologist of the American Institute of Professional Geologists and a Qualified Person under NI 43-101.

Craig Hart is the director of Mineral Deposit Research Unit (MDRU) at the University of British Columbia (UBC), where he initiates and facilitates a wide range of mineral exploration industry-sponsored research projects focused on gold and porphyry systems, regional metallogeny, and exploration methods and trains graduate students to excel in the mineral exploration industry. Craig has degrees from McMaster University, (B.Sc., 1986), University of British Columbia, (M.Sc., 1995), and University of Western Australia (Ph.D., 2005) separated by employment in industry and geologic surveys. He was previously a senior research fellow at the Centre for Exploration Targeting at the University of Western Australia (UWA) in Perth, where he pursued research on the gold metallogeny of China and Mongolia. Most of his early career was with the Yukon Geological Survey, where he undertook regional mapping and metallogenic research in the northern Cordillera. His significant research impacts are in developing intrusion-related gold models, understanding redox controls on intrusion-related metallogeny, and developing plutonic systems in cordilleran-type orogens. Craig has considerable field and mapping experience, which he integrates with geochronology, geochemistry, and geophysics to develop new exploration concepts and targets. He has contributed the training of more than 40 M.Sc. and Ph.D. students and 20 postdoctoral fellows and research associates. He has given numerous invited scientific presentations and short courses throughout the world. He was awarded the Bolyd Award in 2005 by the Geological Association of Canada for best presentation, was the 2010 Society of Exploration Geologists Distinguished Lecturer, and was a top-five finisher for the Audience Choice Award for the Integra Gold Rush Challenge in 2016.

Al Hofstra is a research geologist at the U.S. Geological Survey in Denver, Colorado. He received a B.A. degree from Colorado College, an M.S. degree from the Colorado School of Mines, and a Ph.D. degree from the University of Colorado. His multidisciplinary dissertation on the Jerritt Canyon district led to his involvement in studies of Carlin-type and Carlin-like gold districts in Nevada, USA, and several other countries with an array of students, postdocs, professors, and industry colleagues. He would like to acknowledge his coauthors, the Survey for supporting such research, and those in each study area that made these investigations possible. Al continues a long-standing interest in fluid inclusions as coordinator of the Denver Inclusion Analysis Laboratory. In recent years, his research has expanded into studies of critical elements in myriad deposit types.

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**John Muntean** is an associate professor with the Nevada Bureau of Mines and Geology at the University of Nevada Reno (UNR), where he is the Arthur Brant Chair in Exploration Geology and serves as the director for the Center for Research in Economic Geology (CREG). CREG is a partnership between UNR, the Nevada mining industry, and the U.S. Geological Survey. These partners pool their resources to fund graduate student research that is both fundamental in understanding the genesis of minerals deposits and applicable to the discovery and production of mineral deposits. John received his B.S. degree from Purdue University, his M.S. degree from the University of Michigan, and his Ph.D. degree from Stanford University. Before joining UNR in 2005, John worked 12 years for companies in the mining industry, including Santa Fe Pacific, Homestake, and Placer Dome, mainly exploring for gold in Nevada. His research focuses on Carlin-type, epithermal, and porphyry gold deposits. It aims to assist both exploration and further understanding of processes that control ore formation at all scales. He is an active member of the Society of Economic Geologists and the Geological Society of Nevada. He has been an author or coauthor of 42 peer-reviewed papers and maps, as well as over 50 nonrefereed reports.

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**Moira Smith** is the vice president of exploration geoscience for Liberty Gold Corp., with responsibility for advancing the company’s gold properties in Utah, Nevada, and Idaho. She was previously the chief geologist in Nevada for Frontier Gold, with responsibility for advancing the Long Canyon gold deposit, which created most of the value around Frontier’s 2011 sale to Newmont for 2.2 billion dollars. Prior to Frontier Gold, she served as U.S. exploration manager, senior geologist, and project manager for Teck, where she managed exploration programs for several high-profile, advanced-stage projects throughout the Americas, including the 5.5 Moz Pogo gold deposit, now in production, the 1.5 billion tonne Petaquilla Cu-Mo-Au porphyry deposit in Panama, and the 3.5 Moz El Limon gold deposit in Mexico, also in production. Moira has a Ph.D. degree in geology from the University of Arizona, and is a registered PGeo. (British Columbia). She has held board or executive positions with numerous industry associations and is a past Councilor and Fellow of the Society of Economic Geologists. Moira is a member of the technical advisory board for Discovery Metals Corp.
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Qingping Tan received his B.S. degree in mineral resource exploration engineering from Liaoning Technical University, China, and a Ph.D. degree in mineralogy, petrology, and economic geology from the Chinese Academy of Sciences. He began his career at the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, as a postdoctoral fellow from 2015 to 2017. From 2017 to present, he worked in the Institute of Geochemistry, Chinese Academy Sciences, as a postdoctoral fellow. He has participated in regional mineral resource studies in the Qinling area. His recent research work has focused on establishing a 3-D model of typical Carlin-type Au deposits in Guizhou, China.

Dan Topa conducted his Ph.D. studies on the mineralogy, crystal structure, and crystal chemistry of the bismuthinite-alkinite series at the University of Salzburg in 2001 after obtaining a diploma degree in solid state physics in 1980 from the University of Bucharest. Since his promotion, he has been involved with the electron microprobe at the University of Salzburg and recently at the Natural Science Museum of Vienna studying the crystal chemistry and structure of the sulfoalts.

Michael Tucker received his B.Sc. degree at Laurentian University in 2010 and his M.Sc. degree at the University of British Columbia in 2015. He has worked in the mineral exploration industry through his studies from 2007 to the present day. He has worked throughout Canada on a variety of commodities, with specialties in Cordilleran gold as well as Abitibi gold and nickel. He continues to be an active member in the Canadian mineral exploration industry.

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Introduction

Diversity of Carlin-Style Gold Deposits

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Carlin-style gold deposits have remained an enigma for economic geologists, despite decades of mining and research. Questions concerning their origin remain, as do questions about why the vast majority of deposits are located in the Great Basin region of the western United States, mainly in Nevada. Though the first Carlin-style deposit in Nevada, White Caps, was discovered near the town of Manhattan in 1917, followed by Gold Acres in 1922, and then Getchell in 1934, it was not until the discovery of the Carlin deposit in 1961 that this enigmatic style of gold mineralization attracted the attention of economic geologists and explorationists. The Carlin deposit contained 156 tonnes (t) (5 Moz) of gold that was amenable to open-pit mining and inexpensively recovered from oxide ore with cyanide. The increase in gold prices in the 1970s led to a modern day gold rush in Nevada, leading to the discovery of dozens of deposits. The discovery of the covered, largely refractory Betze-Post deposit in 1986, with a current endowment (past production and current reserve/resource) of nearly 1,250 t (40 Moz), demonstrated Carlin-style deposits can be giant and that refractory ores could also be very profitable. The current endowment of Carlin-type deposits in Nevada is approximately 7,930 tons (255 Moz). Nearly 90% of that endowment comes from four clusters of deposits: the Carlin trend, Getchell, Cortez, and Jerritt Canyon.

The incredible success spurred some companies to explore for these deposits outside of Nevada. Carlin-style deposits were discovered in many places around the world. Most of the discoveries were spatially and temporally associated with upper crustal intrusions with an accompanying zoned sequence of mineralization styles, hydrothermal alteration, and metals, within which the Carlin-style mineralization was the most distal. More importantly, the deposits did not form in clusters and were significantly smaller than the deposits in Nevada (<100 t or 3 Moz). Carlin-style deposits more similar to those in Nevada were recognized in China in the 1980s, and a string of prospects with Carlin-style mineralization even more similar to deposits in Nevada were discovered in the Yukon starting in 2008.

In May of 2015, John Muntean and Moira Smith convened a Society of Economic Geologists forum entitled “Diversity of Carlin-Style Gold Deposits,” which was part of a Geological Society of Nevada symposium. The objective was to better understand the critical differences and similarities with the large deposits in Nevada and other deposits in western North America and the rest of the world. The papers in this volume are based on the research that was presented at the forum.

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Hofstra and Cline (2000), the portions of distal disseminated deposits hosted by carbonate-bearing rock types can strongly resemble Carlin-type deposits. However, temperatures can be higher than Carlin-type gold deposits, and ore fluids commonly have a significant component of magmatic-hydrothermal fluids based on stable isotopes. Arsenopyrite is common, and the total amount of sulfide is typically higher as well. Other styles of mineralization can contribute to ore, including polymetallic (Ag-Pb-Zn-Cu-Sb-Mn-Te), vein, and disseminated mineralization, in which gold occurs as native gold or electrum. “Distal disseminated gold ± silver deposit” is proposed here for these deposits, and “Carlin-style” will be used for the portion of the deposit that resembles Carlin-type gold deposits.

In addition, some low-sulfidation epithermal deposits of late Eocene to Pliocene age occur in Nevada and share features of Carlin-type gold deposits, especially if they are hosted by carbonates and calcareous siliciclastic rocks (Hofstra and Cline, 2000). Like Carlin-type gold deposits and distal disseminated gold ± silver deposits, ore commonly has the same structural and stratigraphic controls. These deposits are commonly associated with jasperoid, decarbonatization, and argillization. Jasperoid is much more common in the epithermal deposits. The jasperoids are commonly veined and/or hydrothermally brecciated, with open space filled by quartz, calcite, and/or adularia with textures indicative of boiling, which are typically absent in Carlin-type gold deposits. The epithermal deposits commonly have a Au-As-Hg-Tl geochemical signature but, in addition, commonly contain strongly anomalous Se, Cu, Pb, Zn, and Mn. Gold typically occurs as free electrum but can occur in solid solution in arsenian pyrite or arsenopyrite (John et al., 2003). High-sulfidation epithermal deposits that form in carbonates and calcareous siliciclastic rocks can also resemble Carlin-type gold deposits. Sericitic and advanced argillic alteration in quartzofeldspathic rocks is typically expressed as silica-pyrite bodies in carbonates (Einaudi, 1982). Silica-pyrite bodies resemble jasperoid but contain much more pyrite (commonly >-10 vol %) than jasperoid associated with Carlin-type gold deposits (typically <-3 vol %). As for distal disseminated gold ± silver deposits, “epithermal” should be used for the deposit, and “Carlin-style” for the portion that resembles Carlin-type gold deposits.

As mentioned above, there is likely a spectrum of deposits that have characteristics that vary between those of Carlin-type gold deposits and distal disseminated gold ± silver deposits, between those of Carlin-type gold deposits and epithermal deposits, and between those of distal disseminated and epithermal deposits (Fig. 1). For example, Johnston and Ressel (2004) and Johnston et al. (2008) were the first to point out a possible continuum between Carlin-type gold deposits and distal disseminated deposits, with the continuum controlled by the distance the deposits were to intrusions. They highlighted the Cove distal disseminated gold-silver deposit as an example of a continuum between polymetallic gold-silver-bearing veins and mantos and Carlin-style gold mineralization, where arsenian pyrite contains both gold and silver. Later, Muntean et al. (2017) demonstrated that Carlin-style mineralization overprints the polymetallic mineralization at Cove. In addition, the Au/Ag ratios of Carlin-style mineralization at Cove increase, and the pyrites take on textures of Carlin-type gold deposits with increasing distance from the overprinted polymetallic mineralization.

Fig. 1. Schematic crustal cross section showing the possible interrelationships between various sources of ore fluids and types of Carlin-style gold deposits (yellow), highlighting the possible continua in features and processes between Carlin-type deposits and distal disseminated deposits associated with porphyry systems and epithermal systems.
The same type of spectrum likely exists between Carlin-type gold deposits and epithermal deposits in Nevada. In the Carlin-type gold deposits at Alligator Ridge, preore Eocene fluvial conglomerates and lacustrine sediments proximal to the deposit are silicified and have the same Carlin-type geochemical signature as ore at Alligator Ridge, containing up to 32 ppb Au, 447 ppm As, and 24 ppm Hg (Nutt and Hoftstra, 2003). Jasperoid breccias locally have textures consistent with hydrothermal breccias, including rounded clasts, upward transported clasts, and rock flour matrix (Tapper, 1986). Similarly, at the south end of the Carlin trend, Eocene conglomerates are silicified and anomalous in As and Hg (Ressel et al., 2015). Based on structural reconstructions, these mineralized Eocene sedimentary rocks were about ~100 to 150 m above the Carlin-type ore at Emigrant. At the Pinon deposit farther to the south, jasperoids are cut by banded colloform quartz-chaledony veins with barite and stibnite (Hollingsworth et al., 2017).

**Overview of the Volume**

The volume is organized into 10 chapters. The first four chapters are on Carlin-type gold deposits in Nevada. In chapter 1, Cline (2018) reviews advances in the understanding of Carlin-type gold deposits since the publication of Cline et al. (2005), particularly for the deposits in Nevada. Advances that are highlighted include the application of sequence stratigraphy to better understand and predict how carbonate facies control mineralization (Cook, 2015). Regional studies have offered evidence for possible reactivation of Neoproterozoic basement structures related to continental rifting, forming linked basement-upper crustal faults that served as primary conduits for ore fluid (Ensmbo et al., 2006; Muntean et al., 2007). District studies have resulted in a greater awareness of the importance of relaxed, preore contractional structures in controlling ore during a change from contractional to extensional tectonics (Rhys et al., 2015). Other advances include the realization that the Carlin trend is underlain by an Eocene batholith that overlapped formation of Carlin-type gold deposits in both time and space, based on Eocene dikes that both predate and postdate mineralization (Ressel and Henry, 2006). Detailed geochronology indicates both magmatism and ages of Carlin-type gold deposits young from northeast to southwest due to slab rollback and removal (Ressel and Henry, 2006; John et al., 2008). Apatite fission track data indicate the giant Betze-Post orebody formed in <15,000 to 45,000 years (Hickey et al., 2014b). Detailed studies of ore-stage arsenian pyrite show that trace element and sulfur isotope zoning formed from temporally discrete ore fluids fed by separate structures (Barker et al., 2009; Longo et al., 2009; Muntean et al., 2009). Recent research also focused on enlarging the target for Carlin-type gold deposits by looking for zoning patterns surrounding Carlin-type gold deposits, including lithogeochemistry (Patterson and Muntean, 2011) and halos of depleted δ18O in carbonate oxygen isotopes (Barker et al., 2013; Hickey et al., 2014a; Vaughan et al., 2016), as well as signatures in transported alluvial and sedimentary cover and groundwater (Muntean and Taufin, 2011; Cluer, 2012). In chapter 2, Muntean (2018) presents a mineral systems approach to exploring for Carlin-type gold deposits in Nevada. He first lays out critical processes for formation of Carlin-type gold deposits: (1) sources of gold and components of ore fluids, (2) formation of fluid pathways, (3) water-rock interaction and gold deposition, and (4) a tectonic trigger. The critical processes are then converted into a practical targeting system for Carlin-type gold deposits, ranging from regional to district to drill target scales. The critical processes of the Carlin mineral system are translated into targeting elements and mappable targeting criteria.

The next two chapters are on deposits over which there has been debate as to whether they are Carlin-type gold deposits as defined above. The four large clusters of Carlin-type gold deposits in Nevada are hosted in carbonates that were deposited along the slope or near the shelf-slope margin. However, recent discoveries have generated more exploration on the carbonate shelf to the east of the large Carlin-type gold deposits. In chapter 3, Smith and Cook (2018) make a convincing argument that the deposits on the shelf are Carlin-type gold deposits. They lay out a predictive stratigraphic framework for exploration on the shelf in the eastern Great Basin. They describe a premise for their paper in which the better the understanding of the origin of rocks and the depositional and postdepositional processes under which they formed, the more accurately geologists can make well-founded stratigraphic, sedimentological, structural, geochemical, and diagenetic interpretations. The Marigold gold deposit has been interpreted in the past to be a distal disseminated gold deposit (Theodore, 2000). Marigold has past production, reserves, and resources totaling nearly 327 t Au (10.5 Moz). Higher-grade ores are hosted by carbonates, but the vast majority of the ore is lower grade and hosted in quartzite and variably calcareous siliciclastic rocks. In chapter 4, Fithian et al. (2018) argue that Marigold is a Carlin-type gold deposit. Similar to Carlin-type gold deposits, gold is present in Au, As, and Sb-rich pyrite rims on pregold-stage pyrite that occurs along fractures and in veins in the quartzite and disseminations in argillized siliciclastic rocks and decalcified carbonates. Deep drilling has confirmed the presence of slope facies carbonates underneath the known mineralization and the Roberts Mountain thrust fault, lending the possibility of a large carbonate-hosted Carlin-type gold deposit underneath the 327 t Au (10.5 Moz) hosted in the predominantly siliciclastic host rocks.

The next three chapters cover the closest analogues to Carlin-type gold deposits outside of Nevada. Chapters 5 and 6 describe the Carlin-type gold deposits in southwest China, and chapter 7 covers Carlin-type occurrences in the Yukon. In chapter 5, Su et al. (2018) present a detailed summary of the current state of knowledge of Carlin-type gold deposits in the Dian-Qian-Gui “Golden Triangle” area of southwest China. Approximately 800 t (25.7 Moz) in nearly 50 deposits in a 300×300-km area makes it the second largest concentration of Carlin-type gold deposits in the world. Based on abundant data, Su et al. (2018) present a model in which the deposits formed in the Late Jurassic-Early Cretaceous from fluids generated during metamorphism during the Yanshanian orogeny. Fluid inclusion data indicate the Carlin-type gold deposits formed at depths of ~2 to 6 km, significantly deeper than Carlin-type gold deposits in Nevada, which typically formed at depths of <~2 to 3 km. In chapter 6, Xie et al. (2018) compare the Shuiyindong and Jinfeng Carlin-type gold deposits in China with the Getchell and Cortez Hills deposits in Nevada, with a focus on ore paragenesis and pyrite chemistry.
Dissolution of carbonate and replacement by quartz requires characteristics do not necessarily mean shared deposit origins. As emphasized by Seedorff and Barton (2005), shared deposit fluid inclusion data from Allchar indicate mixtures of saline mitization. As for Bau and the Iranian deposits, isotopic and content than Carlin-type gold deposits, and has synore dolo-(proximal Au-Sb to distal As-Tl), has a significantly higher Tl and low base metals. However, the deposit is clearly zoned mineralogy (gold-bearing arsenian pyrite), high Au/Ag ratios, strong introduction of Fe, Mn, Pb, and Ag, along with Au, As, and Sb. Most of the gold resides in arsenopyrite rather than in trace element-rich arsenian pyrite. In chapter 9, Dali-ran et al. (2018) present detailed studies of the Carlin-style mineralization at the Aglarreh and Zarshouran deposits in northwest Iran. Most of the gold occurs in arsenian pyrite and sphalerite, and as native gold associated with late-stage As sulfides and cinnabar. Similar to Bau, the authors conclude Aglarreh and Zarshouran are shallow manifestations of intrusion-related hydrothermal systems and, therefore, are best classified as distal disseminated gold ± silver deposits. Strmić Palinkaš et al. (2018), in chapter 10, report on a detailed study of the Allchar gold deposit in Macedonia. Allchar shares many features of Carlin-type gold deposits in Nevada, including alteration (decalcification/silicification/argillization), ore mineralogy (gold-bearing arsenian pyrite), high Au/Ag ratios, and low base metals. However, the deposit is clearly zoned (proximal Au-Sb to distal As-Tl), has a significantly higher Tl content than Carlin-type gold deposits, and has synore dolomitization. As for Bau and the Iranian deposits, isotopic and fluid inclusion data from Allchar indicate mixtures of saline magmatic-hydrothermal fluids and dilute meteoric waters.

**Final Remarks**

As emphasized by Seedoff and Barton (2005), shared deposit characteristics do not necessarily mean shared deposit origins. Dissolution of carbonate and replacement by quartz requires no more than a cooling, mildly acidic hydrothermal fluid. Meteoric, metamorphic, and magmatic-hydrothermal fluids start rising and cooling at very different pressures and temperatures, yet at the conditions of ore formation of Carlin-style mineralization (<300°C and <500 bar) they converge. Thus, similar-looking deposits can have very different origins. The three deposit types described above—Carlin-type gold deposits, distal disseminated deposits, and epithermal deposits—can be considered end members with different origins. Figure 1 schematically illustrates the end members; however, as pointed out above, there could very well be continua between these end members. Future studies should focus on deposits that have characteristics of more than one end member and thus may represent a continuum of processes, such as variable mixtures of meteoric, metamorphic, and magmatic-hydrothermal fluids. A continuum between Carlin-type gold deposits and distal disseminated gold ± silver deposits may simply be a function of the depth from an underlying magma chamber, as proposed by Johnston and Ressel (2004). Likewise, a continuum between Carlin-type gold deposits and epithermal deposits may simply be a function of depth below the paleosurface. The more we study these hybrid deposits, the more we will understand the processes that control these continua, with the ultimate goal of truly understanding the Carlin-type gold deposit end member, including solving the continuing questions regarding the sources of gold in Carlin-type gold deposits.

**REFERENCES**


Cline, J.S., 2018, Nevada’s Carlin-type gold deposits: What we’ve learned during the past 10 to 15 years: Reviews in Economic Geology, v. 20, p. 7–37.


INTRODUCTION: DIVERSITY OF CARLIN-STYLE GOLD DEPOSITS


