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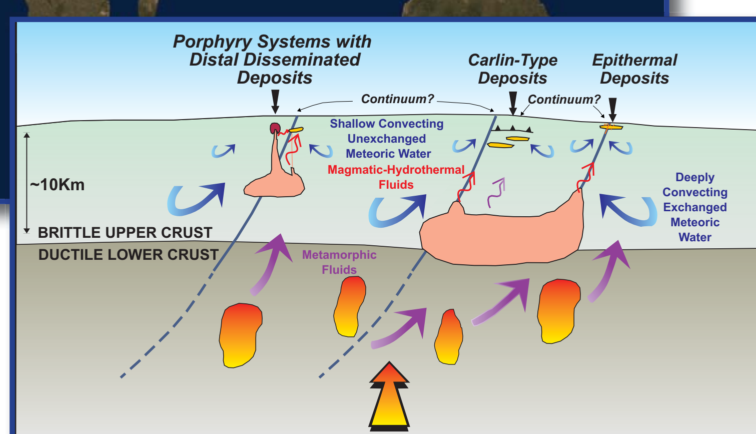
ECONOMIC GEOLOGY
Volume 20

DIVERSITY OF CARLIN-STYLE GOLD DEPOSITS



Editor
John L. Muntean

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University of Nevada Reno

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Published by the Society of Economic Geologists, Inc.
7811 Shaffer Parkway
Littleton, CO 80127, USA

Website: segweb.org
E-mail: seg@segweb.org

Printed by:
robinprint
9457 S. University Blvd., #807
Highlands Ranch, CO 80126-4976
Email: corey@robinprint.com

ISSN
0741–0123 (Print)
2374–443X (PDF)

ISBN
978–1–629492–22–3 (Print)
978–1–629495–78–1 (PDF)

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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PREFACE

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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for its support of this volume.

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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 Boldy 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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Reviews in Economic Geology, v. 20, pp. 1–5

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.

Terminology

Differences between the majority of Carlin-style deposits in Nevada and other Carlin-type deposits led to a proliferation of terms, including Carlin-type, Carlin-like, Carlinesque, sedimentary rock-hosted gold deposits, and distal disseminated deposits, among others. The plethora of terms has led to much confusion. This is not surprising, given the inclination of economic geologists to pigeonhole ore deposits into deposit types and, in so doing, underappreciate the spectra of hydrothermal processes than can lead to continua of deposits that share characteristics of established deposit types. An attempt is made here to reestablish a terminology for Carlin-style deposits, building off the framework developed by Hofstra and Cline (2000).

The four main clusters of deposits that account for the vast majority of Carlin-type gold deposits—the Carlin trend, Getchell, Cortez, and Jerritt Canyon—remarkably share many features, as first pointed out by Hofstra and Cline (2000) and highlighted by Muntean et al. (2011). These include similar (1) tectonic setting, (2) carbonate host rocks, (3) replacement mineralization, with structural and stratigraphic ore controls and a lack of veins, (4) hydrothermal alteration characterized by dissolution and silicification of carbonate and argillization of silicates, (5) ore paragenesis characterized by auriferous, arsenian pyrite formed by sulfidation during replacement, where the majority of gold is invisible, in the form of Au^{+1} in the pyrite, followed by late orpiment, realgar, and stibnite, (6) Au-Tl-As-Hg-Sb-(Te) geochemical signature in both the ore and ore-stage pyrite that is low in Ag (Ag/Au < 1) and base metals, (7) temperatures and depths of formation (~180°–240°C; <~2–3 km), and (8) lack of clear relationship with upper crustal intrusions, as exemplified by lack of mineralogical or elemental zoning at scales of <5 to 10 km laterally and <2 km vertically. Hofstra and Cline (2000) were the first to use these similar characteristics to formally define Carlin-type gold deposits. Carlin-type gold deposits represent an end member—an obviously important one—to which other deposits should be compared. The two localities in the world that have Carlin-style deposits that are most similar to the Carlin-type end member are the deposits in southwest China and recently discovered prospects in central Yukon. These deposits in China and the Yukon are considered to be Carlin-type gold deposits in this volume.

Most of the other Carlin-style deposits in the world occur on the distal edges of magmatic-hydrothermal systems related to upper crustal intrusive complexes. These Carlin-style deposits were termed "distal disseminated" deposits by the U.S. Geological Survey (Cox, 1992). As outlined by

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doi: 10.5382/rev.20.00; 5 p.

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-Sb-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.

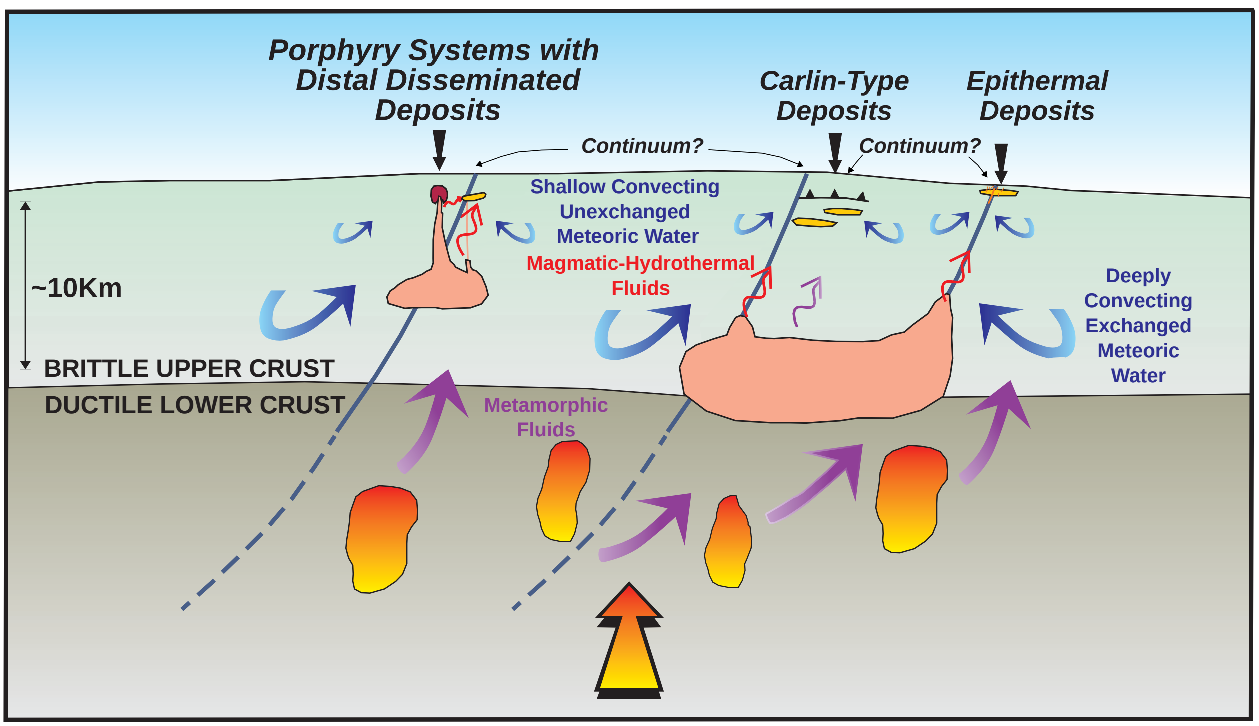

Fig. 1. Schematic crustal cross section showing the possible interrelationships between various sources of ore fluids and types of Carlin-style gold deposits (yellow), highlighting the possible continua in features and processes between Carlin-type deposits and distal disseminated deposits associated 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 Hofstra, 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-chalcedony 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 (Emsbo 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 $\delta^{18}O$ 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 Taufen, 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.

Shuiyindong and Jinfeng contain more euhedral pyrite with significantly less Au, As, Hg, Sb, Tl, and other trace elements than the Nevada Carlin-type gold deposits. Fluids appear to have been more acidic in the Nevada Carlin-type gold deposits, resulting in more carbonate dissolution and argillization characterized by illite and kaolinite. These results are consistent with the conclusions of Su et al. (2018) that the Chinese Carlin-type gold deposits formed at pressure-temperature-chemistry conditions that were intermediate to conditions of the shallower Nevada Carlin-type gold deposits and the more deeply formed orogenic gold systems.

In chapter 7, Tucker et al. (2018) carefully describe several Carlin-type occurrences in the Rackla belt in the Yukon. Based on the descriptions, the occurrences appear to closely resemble the Nevada Carlin-type gold deposits. However, Tucker et al. (2018) point out that the tectonic and magmatic setting during gold mineralization in this remote part of the Yukon is poorly understood. Thus far, little has been uncovered for contemporaneous regional magmatism or tectonism, as is observed for the Nevada Carlin-type gold deposits.

The last three chapters examine distal disseminated gold ± silver deposits. In each of these chapters, the authors make convincing arguments that the Carlin-style mineralization is a distal manifestation of magmatic-hydrothermal fluids exsolved from granitic magmas that mixed with meteoric water. In chapter 8, Percival et al. (2018) present detailed geologic, paragenetic, isotopic, and fluid inclusion data from a variety of mineralization styles that zone outward from subvolcanic Miocene intrusions in the Bau mining district on the island of Borneo in Sarawak, Malaysia. Deposits zone outward from skarn to calcite-quartz veins to Carlin-style mineralization in decalcified/silicified carbonates and variably calcareous siliciclastic rocks. Unlike Nevada Carlin-type gold deposits, there is 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, Daliran et al. (2018) present detailed studies of the Carlin-style mineralization at the Agdarreh 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 Agdarreh 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 Seedorff 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.

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