International Journal of
Earth & Environmental Sciences

Original Article Open Access

The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA

John A. Groff
Tuscaloosa Academy, 420 Rice Valley Road, Tuscaloosa, AL, 35406, USA

Abstract

The genesis of Carlin-type deposits involves a sequence of common steps yet significant differences exist in ore fluid chemistry, the timing of important precursor events, and metal content of host rocks in the Getchell trend vs. Carlin trend. Quadrupole mass spectrometer analyses of fluid inclusion gases in samples of Main ore-stage jasperoid from the Getchell and Goldstrike properties record a CO_2-rich magmatic component based on the distribution of data in N_2–Ar–He ternary diagrams. What distinguishes the hydrothermal systems is a large component of meteoric water at the Goldstrike property versus a basinal fluid for the Getchell property. In contrast, the formation of Main ore-stage jasperoid at the Twin Creeks mine was produced by N_2-rich organic and metamorphic fluids based on stable isotope and gas data. A CO_2-rich magmatic component did not dominate the hydrothermal system until near the end of Main ore-stage and start of Late ore-stage mineralization at Twin Creeks.

Important precursor events to Eocene Carlin-type mineralization in the Getchell trend and Goldstrike property did not follow the same sequence yet produced similar results. During the deposition of Cambrian–Ordovician (Getchell trend) and Devonian (Goldstrike property) rock formations that host Carlin-type mineralization, basement faults were reactivated and caused soft-sediment deformation (e.g., folding, debris flows, and brecciation). Subsequent alteration that produced ferroan carbonates occurred due to Cretaceous and Devonian hydrothermal systems in the Getchell trend and Goldstrike property, respectively. Also, important ground preparation was related to Cretaceous and Jurassic igneous events in the Getchell trend and Goldstrike property, respectively. Although mineralizing events containing small amounts of accessory gold were associated with pre-Eocene igneous events in both areas, only Devonian rocks in the Carlin trend host SEDEX mineralization containing significant gold that was concentrated by circulating meteoric water.

These differences should not alter exploration strategies because the defining characteristics of Carlin-type deposits in Nevada include being located near a craton margin; Precambrian accretion and rifting to create basement structures that were reactivated over time; plate subduction that produced a highly altered and mineralized mantle source area for Eocene melts; the pre-gold formation of ferroan carbonates to accommodate sulfidation; and mineralization on a regional scale.

Publication History:

Received: November 28, 2022
Accepted: February 22, 2023
Published: February 24, 2023

Keywords:

Carlin-type, Geologic evolution, Mineralization, Devonian rocks, Gold deposits

Introduction

North-central Nevada is one of the world's major gold provinces due to the presence of giant Carlin-type (CT) deposits. Although certain aspects of CT deposits are widely accepted, others are debated. Fundamental characteristics that define these deposits are: 1) basement structures that were the locus of igneous–hydrothermal activity overtime; 2) a trace element assemblage of Au–As–Hg–Sb–Tl; 3) the absence of zoning for trace elements and mineralization; 4) alteration consisting of decalcification, argillization, and silicification; 5) gold occurs within arsenian pyrite rims or as micron-sized spheres deposited by sulfidation; and 6) auriferous fluids had temperatures of ~150°–250°C, salinities ≤ 4 wt.% NaCl equiv., and gas concentrations ≤ 4 mol% [1,2]. The timing of mineralization at 42–36 Ma is well established and coincides with a regional Eocene igneous–hydrothermal event in north-central Nevada [3-6].

Aside from these fundamental tenets, debate over genetic models arises due to differences between CT deposits in Nevada and features that are shared with Carlin-style deposits around the world. Examples of the former include liquid hydrocarbons occurring in deposits of the Alligator Ridge district [7]; Au-rich SEDEX mineralization in Devonian rocks that are important hosts for ore in the Meikle and Rodeo CT deposits [8]; and a temporal overlap of CT and low-sulfidation epithermal gold mineralization in the Getchell trend [9](Figure 1). Whereas similarities with Carlin-style deposits in Malaysia and Indonesia include characteristic alteration (e.g., decalcification and silicification), trace element assemblages, mineral paragenesis, and gold deposition by sulfidation. However, outside of Nevada there is geochemical/mineralogical zoning at the deposit scale and Carlin-style mineralization together with skarn and vein deposits are concentrically arranged around stocks that contain Cu-(Mo)-quartz stockworks [10,11].

Such relationships have not been identified in the Carlin and Getchell trends but may exist in the Battle Mountain–Eureka trend. The best example is the McCoy Au–skarn deposit occurring proximal to the Eocene Brown stock with distal Au–Ag–base metal mineralization at

*Corresponding Author: Prof. John A. Groff, Tuscaloosa Academy, 420 Rice Valley Road, Tuscaloosa, AL, 35406, USA; E-mail: jgroff@tuscaloosaacademy.org

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

the Cove deposit and underlying deep high-grade CT mineralization, that has consistent changes in Au-Ag ratios relative to the stock [12] (Figure 1). Although the timing of CT mineralization in all three trends coincides with Eocene igneous activity, the only compelling evidence of a magmatic source for auriferous fluids [1,9,13] is in an area where no Eocene igneous rocks have not been mapped or identified by deep drilling.

The objective of this paper is to show how differences should exist in CT deposits because the local geology and geological history of the major mining districts in Nevada are not identical. Therefore, necessary precursor events likely occurred at different times and in some cases by different mechanisms. Case studies will be presented for the Getchell and Twin Creeks deposits, Getchell trend (GT); then compared with the Goldstrike property (GSP), Carlin trend (Figure 1).

Getchell Trend

Geology

North-central Nevada experienced a protracted and complex tectonic history beginning in the Precambrian. Accretion of Paleoproterozoic terranes to the Archean Wyoming Craton and subsequent rifting of the Laurentian supercontinent occurred at 1–1.3 Ga and 0.6-0.9 Ga [14,15]. The major crustal breaks that resulted became important controls on subsequent sedimentation, igneous activity, and metallogenic processes. Early Paleozoic rock formations in the GT contain soft-sediment deformation features and debris flows that formed at an active basin margin due to the reactivation of basement structures [16]. Rock types that host CT mineralization include continental shelf carbonates and quartzite to deep basin shale and basalt [17].

Carlin-type mineralization in the GT is dominantly hosted by carbonates within the Cambrian Preble and Ordovician Comus formations (Figure 2). The Preble Formation (Fm) consists of a lower phyllitic shale with limited quartzite beds and upper silicified–calcareous shale containing thin limestone beds [18]. Whereas the Comus Fm is represented by an alternating sequence of shale and limestone beds [18]. Important differences in the Comus Fm at the Turquoise Ridge (TRDG) deposit and Twin Creeks mine are the presence of debris flows vs. a greater abundance of mafic flows/ultramafic sills [19-21]. Finally, the Valmy Fm is represented by interbedded chert, siliceous shale, greenstone, and volcanic rocks [18,22] with CT mineralization being structurally controlled.

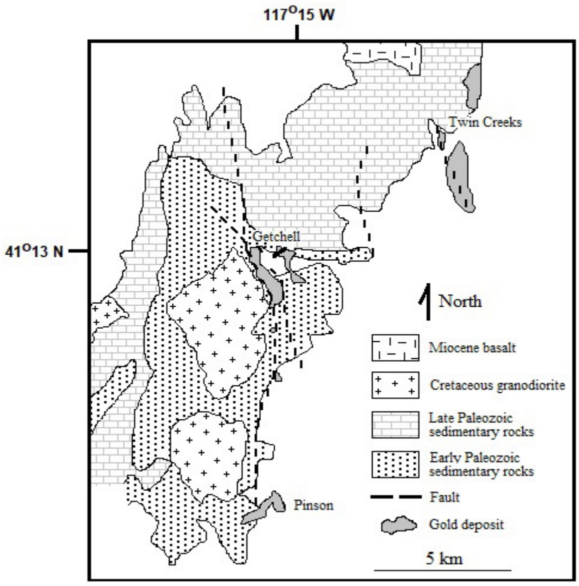

Figure 2: Geologic map of the Getchell trend with locations for the Getchell property and Twin Creeks mine [18,23].

Significant deformation of these rock formations during the Late Devonian–Early Mississippian Antler orogeny produced important ore-controlling structures. This includes the Roberts Mountain thrust fault, which placed nonreactive fine-grained siliciclastic rocks over permeable carbonates [24]. Intense deformation of the Lower-plate rocks is recognized by north (N) to northeast (NE) trending isoclinal

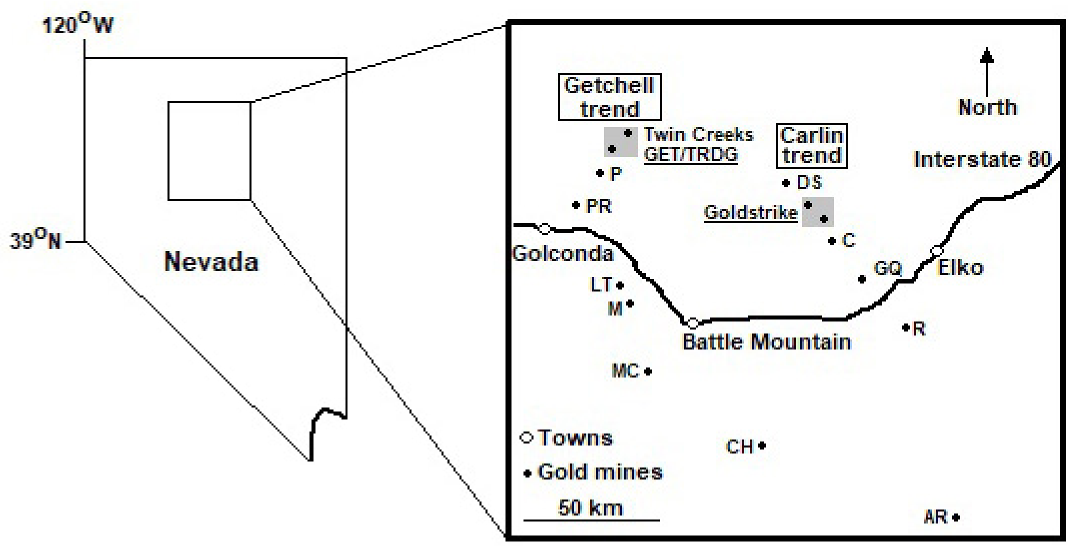

Figure 1: Location map showing towns and Carlin-type deposits that align to form trends in north-central Nevada. Highlighted areas are for the Getchell property and Twin Creeks mine, Getchell trend and Goldstrike property, Carlin trend. Abbreviations for gold deposits: AR = Alligator ridge, C = Carlin, CH = Cortez hills, DS = Dee and Storm, GET = Getchell Main pit, GQ = Gold quarry, LT= Lone Tree, M = Marigold, MC = McCoy and Cove, P = Pinson, Pr = Preble, R = Ren, and TRDG = Turquoise Ridge.

folds overturned to the west [18,25]. An important example at the Twin Creeks mine is the east-verging, overturned Conelea anticline [20,26] that extends the length of the Megapit (Figure 3). A period of uplift and erosion that followed the Antler Orogeny is indicated by the Permian–Pennsylvanian Etchart limestone being deposited on an erosional unconformity [27].

Igneous rocks exposed by mining and identified during deep drilling in the GT are 115–92 Ma granodiorite, dacite, and andesite (Table 1). These are related to eastward-dipping subduction along the western margin of North America that began in the mid-Triassic. The ~92 Ma Osgood Mountains stock is the largest intrusion and bounded on the east side by the ~25 km long Getchell fault zone (Figure 2). This NNW-trending complex of en echelon and sub-parallel faults also controlled the emplacement of associated dikes in the footwall and hanging wall [25]. A notable example being the ~115 Ma dacite dike that served as an important control on the flow of auriferous fluids that formed the TRDG deposit [21]. Cretaceous intrusions at Twin Creeks were also important secondary controls for mineralization as evidenced by a dacite dike in the Vista Vein shear deposit [28].

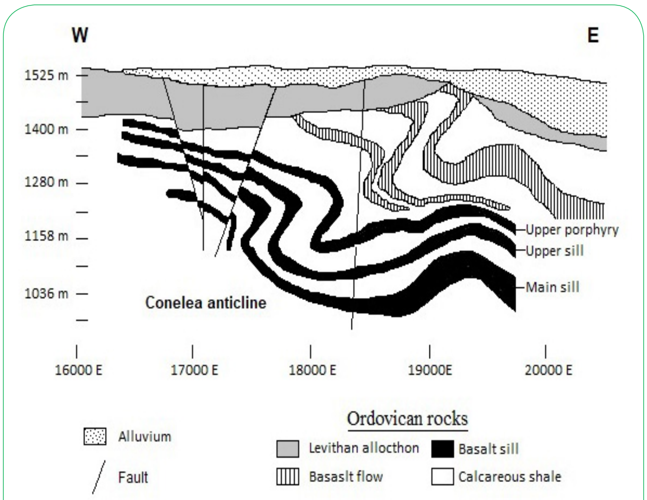

Figure 3: An E-W geologic cross section through the Megapit, Twin Creeks mine [26].

Alteration

Mineralogical and temporally distinct alteration events are recognized in the GT (Figure 4). Propylitization of Ordovician mafic rocks is represented by the assemblage of chlorite–epidote–actinolite that replaces primary orthopyroxenes and possibly represents alteration by seawater [21,29]. In contrast, biotite hornfels formed proximal to the Osgood Mountains stock and 115 Ma dikes at the Getchell and Twin Creeks mines [30,31]. Emplacement of the Osgood Mountains stock also altered rocks of the Cambrian Preble Formation to form an ~3 km wide calcite–wollastonite–diopside–garnet–cordierite–andalusite skarn [32].

Areal extensive 109–103 Ma argillic alteration at the Twin Creeks mine occurred when illite and sericite replaced Fe-rich chlorite in Ordovician mafic rocks (Figure 4). The liberated iron was incorporated by limestone undergoing recrystallization to produce Fe-rich dolomite [33]. Carbonates at the Getchell property were also recrystallized to produce ferroan calcite by the thermal–hydrothermal event associated with the Osgood Mountains stock [21,31]. Spatial relationships suggest sources of iron in the TRDG deposit and Main pit were likely the Ordovician Northern pillow basalt and Cretaceous igneous rocks [21,31], respectively. Additional support for the latter is provided by the replacement of primary biotite by Fe-rich chlorite and then 83 Ma sericite in the Osgood Mountains stock (Main pit) and a dacite dike (North pit; [3]).

Eocene alteration associated with CT mineralization (Figure 4; Table 1) occurs along bedding planes and contacts of rock units, the margins of Cretaceous intrusive rocks, and in structural zones. The decalcification of rock units by acidic hydrothermal fluids increased permeability to enhance fluid flow. Gold ore is commonly associated with silicification (e.g., jasperoid or vuggy quartz) and argillization (e.g., illite and kaolinite; [21,34]).

Age	Method	Description
115 ± 2.3	Zircon U–Pb	Dacite dike
114 ± 2	Zircon U–Pb	Dacite dike
117.3 ± 2.3	Sericite K–Ar	Dacite dike
109–103	Illite $^{40}Ar/^{39}Ar$	Argillized basalt, ultramafic sills
107	Illite K–Ar	Argillized basalt sill
98.4 ± 0.6	Biotite$^{40}Ar/^{39}Ar$	Dacite dike
95.5 ± 1.1	Biotite$^{40}Ar/^{39}Ar$	Dacite dike
95.2 ± 0.6	Hornblende $^{40}Ar/^{39}Ar$	Granodiorite plug
95.1 ± 0.7	Biotite $^{40}Ar/^{39}Ar$	base metal–Au skarn
92.2 ± 2.1	Biotite K–Ar	Dacite dike
91.9 ± 0.6	Biotite $^{40}Ar/^{39}Ar$	Osgood Mtns stock, base metal–Ag–Au skarn
91.9 ± 1.8	Hornblende K–Ar	Andesite dike
91.7 ± 1.8	Sericte K–Ar	Andesite dike
83.1 ± 1.1	Sericite $^{40}Ar/^{39}Ar$	Dacite dike, phyllic alt.
82.3 ± 1.1	Sericite $^{40}Ar/^{39}Ar$	Dacite dike, phyllic alt.
81.4 ± 1.4	Sericite $^{40}Ar/^{39}Ar$	Osgood Mtns stock, phyllic alt.
81.2 ± 1.5	Sericite $^{40}Ar/^{39}Ar$	Osgood Mtns stock, phyllic alt.
80.9 ± 3.3	Sericite K–Ar	Osgood Mtns stock, phyllic alt.
84.3 ± 0.9	K–feldspar $^{40}Ar/^{39}Ar$	Granodiorite plug phyllic alt.
78.4 ± 1.1	K–feldspar $^{40}Ar/^{39}Ar$	Osgood Mtns stock, phyllic alt.
78.1 ± 1.0	K–feldspar $^{40}Ar/^{39}Ar$	Dacite dike, phyllic alt.
74.7 ± 2.2	K–feldspar K–Ar	Altered Osgood Mtns stock
75	K–feldspar modeling	Breccia pipe, qz–py–Au
42.1 ± 0.4	Adularia $^{40}Ar/^{39}Ar$	Epithermal vein
41.9 ± 0.2	Adularia $^{40}Ar/^{39}Ar$	Late-stage Carlin-type
39 ± 2.1	Galkhaite Rb/Sr isotopes	Late-stage Carlin-type

Table 1: A summary of ages for Cretaceous igneous rocks, alteration, and mineralizing events of the GT. Abbreviations: alt = alteration; qz = quartz; py = pyrite; Mtns = mountains. Data are from Silberman et al. [35], Berger and Taylor [25], Osterberg and Guilbert [36], Groff et al. [3], Hall et al. [37], Tretbar et al. [6], Breit et al. [27], Cassinerio [38].

Mineralization

Multiple episodes of mineralization occurred during the Cretaceous igneous–hydrothermal event (Figure 4; Table 1). At the Twin Creeks mines, a 0.6-m wide metamorphic quartz vein contains < 1 ppm Au and hosts CO_2- and CH_4-rich fluid inclusions but is not located within a structural zone or overprinted by CT mineralization [39].

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

Skarn-type mineralization in a sheared Ordovician basalt ~4 km NW of the Main pit, Getchell property is characterized by pyrrhotite–chalcopyrite–arsenopyrite–gold (≤ 3 ppm) and $^{40}Ar/^{39}Ar$ dating of hydrothermal biotite yielded an age of 95.5 Ma [3]. Quartz–base metal mineralization is closely associated with ~115 Ma dikes at the Twin Creeks mine [28] and the ~92 Ma Osgood Mountains stock [35]. Assays of select samples of quartz veins and mineralized calc–silicate skarn record values of ≤ 90 ppm Ag [40] and ≤ 2.5 ppm Au [3].

The final Cretaceous mineralizing events (Figure 4; Table 1) are not associated with specific intrusions. A tectonic breccia in the Main pit, Getchell mine cuts the calc-silicate skarn that formed adjacent to the Osgood Mountains stock. The siliceous matrix contains 0.4 ppm Au and is nearly black due to high concentrations of pyrite and coarse arsenopyrite crystals (≤ 4 mm; [39]). However, it is unknown if the gold occurs in the quartz or sulfide minerals. The emplacement of two breccia pipes at ~75 Ma represents the final Cretaceous mineralizing event (Figure 4). These high-angle narrow bodies in the underground, Getchell mine were not overprinted by CT mineralization and contain 1–3 ppm Au over a vertical interval of ~50 m [3]. The siliceous matrix is nearly black due to abundant fine-grained anhedral pyrite, but the siting of gold in samples was not determined.

Carlin-type ores have distinct textures and mineralogy (Figure 4). Main ore-stage mineralization consists of fine-grained jasperoid, nondescript argillized rocks, and vuggy or sandy quartz in highly decalcified zones [34, 21]. Gold-rich arsenian pyrite at both the Getchell property and Twin Creeks mine occurs as thin rims on pre-existing pyrite crystals and micron-sized fuzzy spheres [26,42].

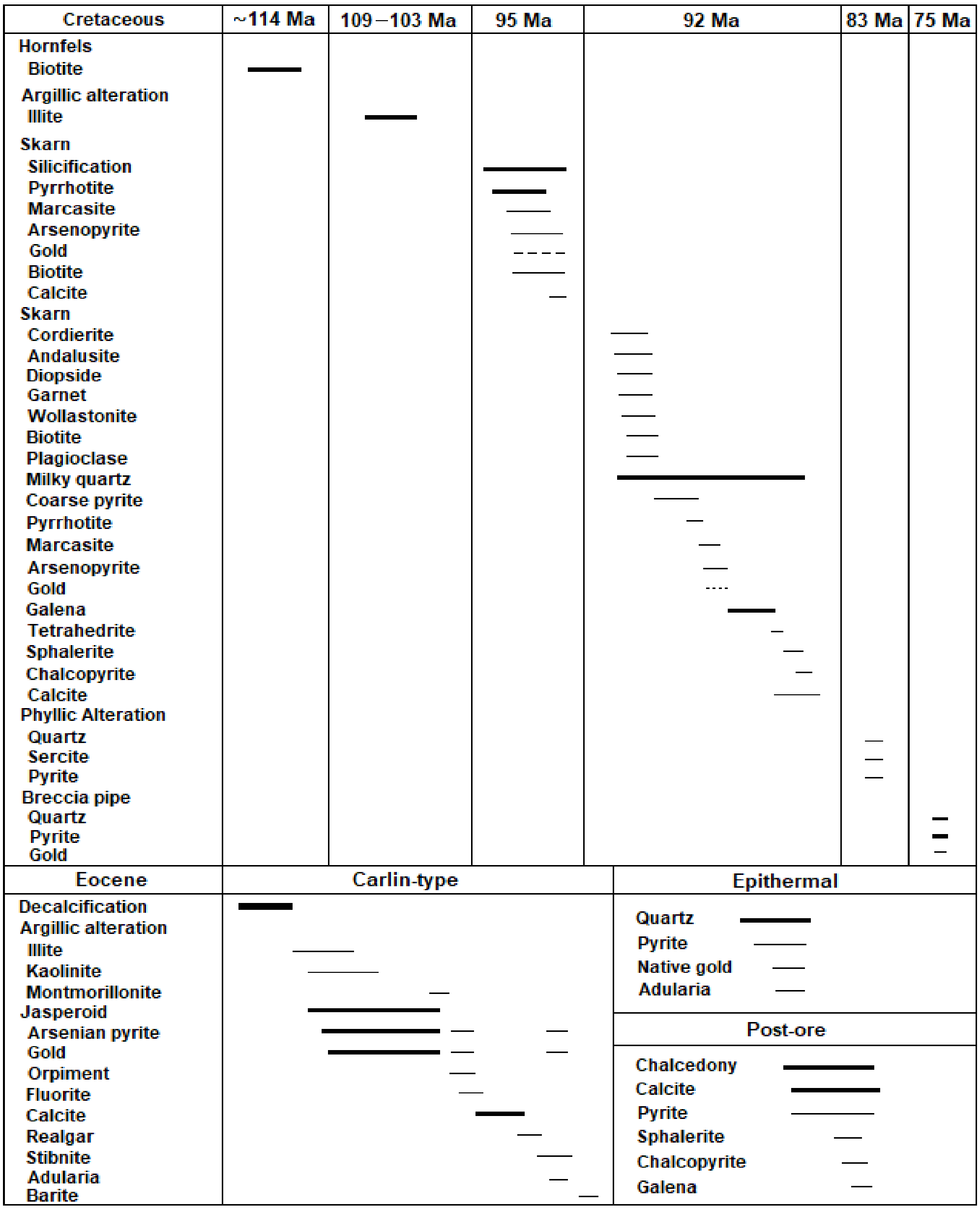

Figure 4: Paragenesis of mineralization and alteration events in the Cretaceous and Eocene for the Getchell property and Twin Creeks mine. Data are from Groff [41], Shigehiro [13], Cail and Cline [34], Fortuna [29], Cassinerio [38], Eck [31], and Barber [28].

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

Late ore-stage mineralization is represented by veins, open-space fillings, or the matrix to breccias (Figure 4). Megascopic arsenic sulfide minerals are most abundant in the Main pit, Getchell mine with massive orpiment veins up to 1.5 m wide [41]. Gold occurs with extremely fine-grained pyrite in orpiment based on SEM element mapping of samples from the Twin Creeks mine [43]. A final CT gold-mineralizing event at the Twin Creeks mine is represented by an ~1.5 m-wide stibnite vein containing intergrown fine-grained pyrite–quartz–adularia [44]. However, CT mineralization transitioned to a low-sulfidation epithermal system represented by stockwork quartz veins in the NE-trending DZ fault zone, Twin Creeks mine [9]. These veins contain disseminated native gold and adularia that has an $^{40}Ar/^{39}Ar$ plateau age indistinguishable from adularia intergrown with CT mineralization (Table 1).

Post-ore mineralization was only identified in the Main pit, Getchell mine as 1–5 cm veins of banded chalcedony and calcite containing disseminated base metals (Figure 4). These veins are located in the hanging wall of the Getchell Fault and can occur as rounded fragments within fault gouge [3].

Goldstrike property, Carlin Trend

Geology

Devonian rock formations that are part of the lower plate of the Roberts Mountain thrust fault represent the dominant host for CT mineralization (Figure 5). There are stacked ore zones within the Betze deposit that progress up-section from the Roberts Mountain Fm to the Popovich Fm and Rodeo Creek Fm. The Roberts Mountain Fm is a laminated dolomitic limestone that contains sedimentary breccia in the top part. An upper and lower unit have been defined for the Popovich Fm. The upper unit consists of a medium- to thin-bedded carbonaceous micritic limestone containing diagenetic pyrite. Whereas the lower unit has planar–wispy laminae in a sandy, bioclastic dolomitic limestone [45,46]. Soft-sediment deformation features and sedimentary breccias are common [47]. A transition zone between the Popovich and Rodeo Creek formations is recognized by bedded siltstone, sandstone, chert, argillite, slaty mudstone, and fossiliferous–muddy limestone [48].

Deformation of these rock formations is extensive and associated with the Late Devonian–Early Mississippian Antler orogeny. Orebodies parallel NNW-trending anticlines (e.g., Post and Betze), faults (e.g., Post and JB), and occur within a structurally complex zone of the Peters syncline where alteration and deformation were focused at the transition between rocks of the Popovich and Rodeo Creek formations [49,50]. Gold mineralization is dominantly hosted by sedimentary and tectonic breccias [47], including the Dillion deformation zone that consists of a tectonic breccia within the sedimentary transition from Popovich Fm to Rodeo Creek Fm.

Two episodes of igneous activity are recognized at the GSP and the dominant one occurred during the Jurassic [52]. This is represented by the ~158 Ma Goldstrike stock (Figure 5) with associated NW-striking lamprophyre and N-striking rhyodacite dikes. Although all Jurassic igneous rocks can be mineralized depending on iron content and permeability, they were more important as secondary controls on the flow of auriferous fluids [52, 53]. An example is at the Meikle mine, where unreactive monzonite acted as an aquitard and focused fluid flow along the dike margin [54].

Eocene intrusions consist of porphyritic dacite dikes that were emplaced between 39–38 Ma [52]. They are inferred to be associated with a deeper plutonic complex identified by a 700 km^2 aeromagnetic anomaly [55]. Radiometric $^{40}Ar/^{39}Ar$ ages of secondary illite in mineralized dikes overlap with emplacement ages [52].

Mineralogical and temporally distinct alteration events occurred from the Devonian–Eocene (Figure 6). The reactivation of basement structures during the Devonian focused fluid flow along basin margins that altered carbonates to create ferroan dolomite (e.g., the zebra dolomite; [54]). Subsequent burial related to the emplacement of the Roberts Mountain allochthon during the Antler orogeny caused the thermal maturation of organic material and migration of petroleum in the Early Mississippian [54]. Cryptocrystalline graphite formed at temperatures of 250°-300°C and alteration includes pumpellyite–actinolite and lowermost greenschist facies [56].

Jurassic intrusive activity and specifically the emplacement of the ~158 Ma Goldstrike stock produced a zone of contact metamorphism ~230-m wide (Figure 5 and Figure 6). Initial alteration consisted of

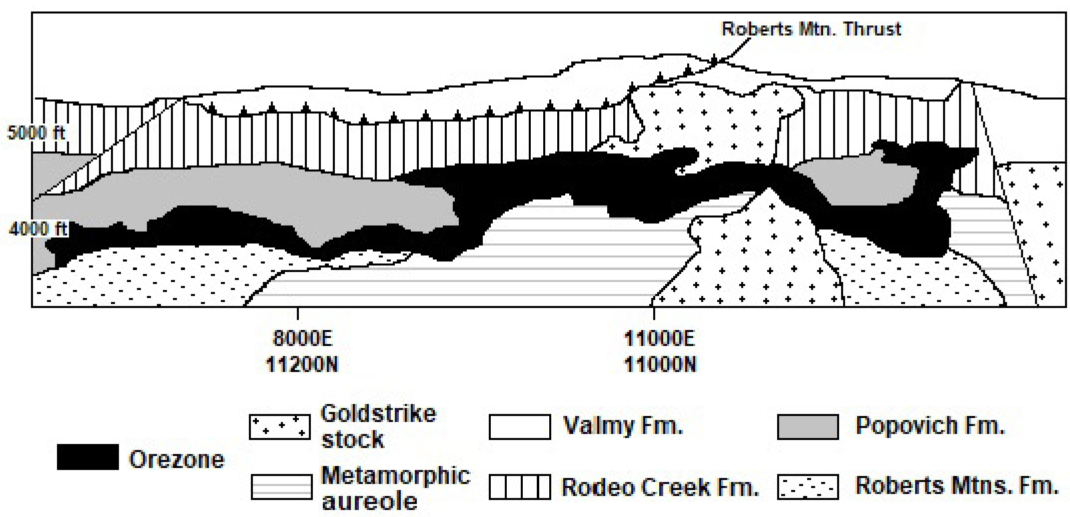

Figure 5: Geologic cross section through the Betze pit, Carlin trend [51].

pyroxene–biotite hornfels and marble that was overprinted by two skarn types: 1) diopside–grossular–vesuvianite, and 2) tremolite–epidote–calcite–diopside with K-feldspar [57]. Alteration of the stock at ~154 Ma resulted in the formation of sericite [54]. A second generation of sericite formed at ~117 Ma based on ages of hydrothermal sericite [58].

Eocene alteration is characteristic of CT deposits (Figure 6). Decalcification increased the porosity of carbonate units to the point that collapse breccias formed at the Meikle mine [47]. Argillization of sedimentary rocks and dikes produced illite, with lesser amounts of kaolinite [52,53]. Whereas gold-mineralization in dikes is associated with the assemblage quartz–pyrite–sericite [52]. Silicification is recognized by fine-grained quartz and veinlets. Multiple stages of silicification are common and work by Leonardson and Rahn [59] identified five stages in areas of the Betze–Post deposit.

Mineralization

Significant gold mineralization prior to Eocene CT exists in the upper mud member of the Devonian Popovich Fm. This syn-depositional SEDEX mineralization includes sphalerite–galena–tetrahedrite–pyrite–chalcopyrite–quartz with gold grades ≤ 68 ppm. Sporadic gold values also occur in polymetallic veins associated with the Jurassic Goldstrike stock (Figure 6) [61].

Paragenetic relationships for Eocene mineralization are best documented by crosscutting veinlets in mineralized dikes of the Meikle and Griffin deposits [52]. Stage 1 veinlets represent Main ore-stage and contain sooty pyrite–arsenian pyrite–arsenopyrite–white mica (sericite and illite)–rutile–replacement quartz (Figure 7). Whereas Stage 2 veinlets are characterized by Ag and Sb sulfosalts–quartz–pyrite–native silver–chalcopyrite. Post-ore Stage 3 veinlets consist of barite–calcite–euhedral pyrite (Figure 7).

Mineralization in the larger Betze–Post deposit was categorized by mineralogy and alteration types to distinguish five types of oreshoots [47,50,59]. Type 1 oreshoots are siliceous, contain rutile, gold occurs in arsenic-rich rims on pre-existing pyrite crystals, and are the highest grade. Type 2 oreshoots are the largest in a volumetric sense and comprised of illite (clay) and carbonaceous material, with gold occurring in arsenian-pyrite rims. Type 3 realgar and orpiment oreshoots often overprint Type 2 oreshoots. Type 4 stibnite–siliceous oreshoots are small and contain the lowest gold grades. Stibnite crystals host inclusions of low-As pyrite and sphalerite. Type 5 polymetallic oreshoots are proximal to the contact of the Goldstrike stock, crosscut other types of oreshoots, and contain a diverse mineral assemblage. This includes pyrite–sphalerite–galena–chalcopyrite–cinnabar–native gold mineralization.

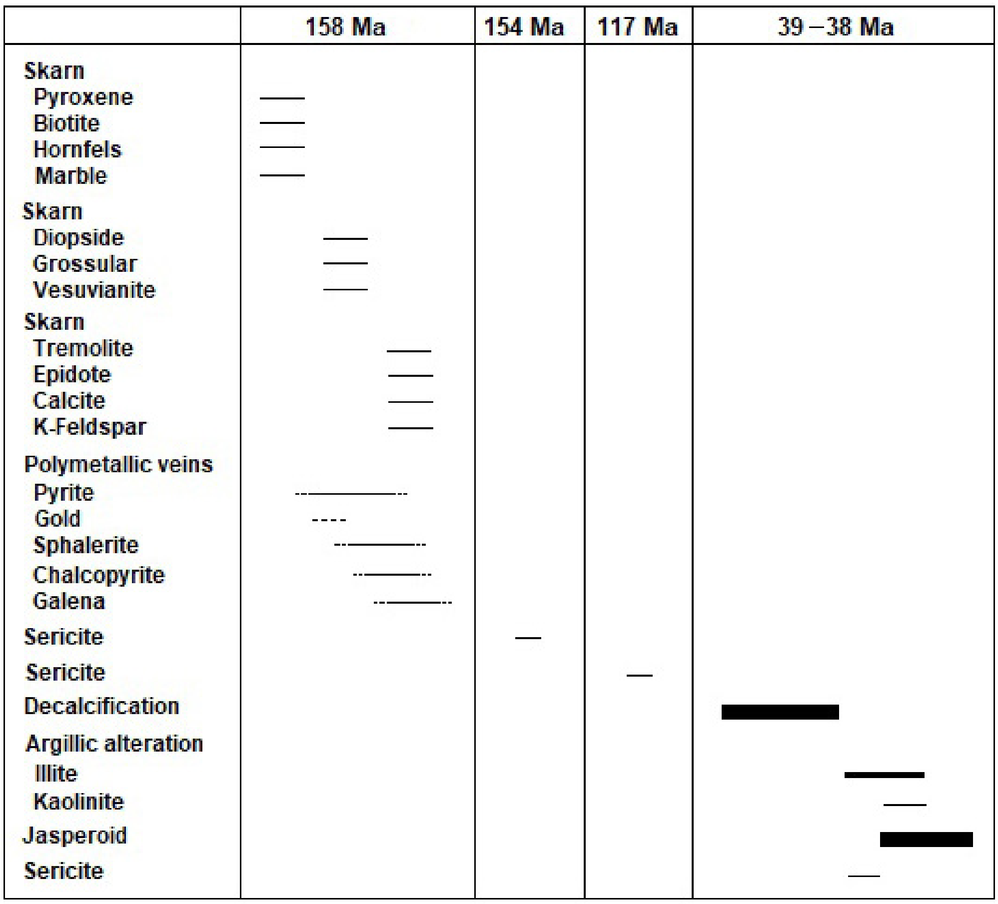

Figure 6: Mineral paragenesis for Cretaceous alteration events, polymetallic veins, and Eocene alteration at the Goldstrike property. Data are from Walck [57], Arehart et al. [58], Ferdock et al. [60], Emsbo and Hofstra [61], Ressel et al. [52], and Emsbo et al. [62].

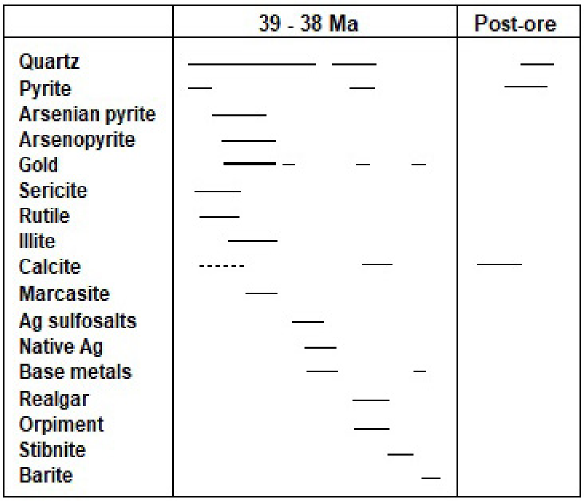

Figure 7: Paragenesis for Eocene mineralization in the Meikle and Betze mines. Data are from Ressel et al. [52], Peters [50], Ferdock et al. [60], Peters et al. [47], Peters et al. [53], and Emsbo[8].

Discussion

Structural preparation

The early structural evolution of the GT and GSP (Carlin trend) was analogous, until the Jurassic. Accretion of the Archean Wyoming craton with subsequent rifting that ended ≥ 0.6 Ga [14,15] created basement structures that were reactivated during the deposition of sedimentary rocks to produce soft-sediment deformation [21,47]. Then significant folding and faulting during the Antler orogeny [18,49] occurred prior to the emplacement of nonreactive fine-grained siliciclastic rocks over permeable carbonates by the Roberts Mountain thrust fault [24].

When mid-Triassic subduction began off the west coast of North America, the Carlin trend became more active in a geologic sense compared with the Getchell trend. At the GSP this is represented by the emplacement of Jurassic intrusions (e.g., the 158 Ma Goldstrike stock); ~117 Ma phyllic alteration associated with Cretaceous igneous activity in the surrounding Carlin trend [58]; and the intrusion of Eocene dikes related to a deeper plutonic complex (Figure 6; [63]). In contrast, the GT experienced an ~40 m.y. Cretaceous igneous–hydrothermal event (Table 1) and CT mineralization occurred distal to any known center of Eocene igneous activity.

Yet the Jurassic and Cretaceous intrusive rocks in both trends served a similar function for ore genesis. The impermeable crystalline rocks were important secondary controls on the movement of auriferous fluids and provided rheological contrasts with sedimentary rocks that resulted in the formation of secondary structures during deformation, which increased permeability [52,1].

A structural difference is the importance of NE–trending faults during mineralization in the GT. These structures likely represent Riedel shears [19] that formed after emplacement of the ~92 Ma Osgood Mountains stock and prior to 42 Ma CT gold mineralization [20]. The faults served as fluid conduits based on microthermometric data that record higher homogenization temperatures (T_h) and salinities for fluid inclusions in Late ore-stage orpiment samples from the TRDG Fault; gas-rich inclusions in samples of jasperoid and orpiment from the Getchell mine that record episodic boiling during mineralization; veins of quartz–adularia–gold ± stibnite that occur within or proximal to NE-trending faults at the Twin Creeks mine; and organic–metamorphic fluids with depleted δD values that are restricted to NE-trending faults at the Twin Creeks mine [9,64]. Why there was a divergence in the structural evolution of these two areas of northern Nevada could be due to different regional stress fields related to subduction, since deposits defining the GT have a NE alignment compared with a NW alignment in the Carlin trend.

Precursor alteration

The most-important precursor alteration event in both the GT and GSP was the formation of ferroan carbonates. This is due to acidic ore fluids dissolving ferroan carbonates and releasing iron, which served as a fundamental component for the deposition of gold by sulfidation. However, the geologic events that formed ferroan carbonates in the two areas were temporally distinct and involved different processes.

Ferroan carbonates in the GT formed during the ~40 m.y. Cretaceous igneous–hydrothermal event. At the Twin Creeks mine, this occurred with argillic alteration from 109–103 Ma [29]. Whereas at the Getchell property, ferroan carbonates likely formed in association with the emplacement of the Osgood Mountains stock and 83 Ma phyllic alteration [3,38]. As ferroan carbonates are the principal host for CT mineralization [65], this alteration represents a critical step in ore genesis.

Extensive sections of ferroan carbonates did not form in association with a Jurassic or Cretaceous igneous–hydrothermal event at the GSP, but rather during Devonian basin evolution. The reactivation of basement faults caused both deformation (e.g., debris flows) during the deposition of sedimentary rocks and focused the flow of hydrothermal fluids along basin margins. This resulted in the formation of ferroan carbonates and SEDEX mineralization containing high gold values. However, two episodes of sercitic alteration at ~154 Ma and 117 may have replaced iron-rich minerals in older intrusive rocks to form ferroan carbonates on a smaller scale, such as at the Getchell property.

Additional precursor alteration that impacted ore genesis was widespread argillization and skarn formation. At the Twin Creeks mine, argillic alteration of mafic sills between 109–103 Ma produced laterally extensive, impermeable zones overlying permeable carbonate units. Although the margins of the argillized sills are weakly mineralized, they served as a primary control on the flow of ore fluids beyond structural zones [20]. A decrease in the permeability of country rocks in both the GT and GSP also occurred due to skarnification, yet there was a corresponding increase in brittleness. Therefore, subsequent deformation produced breccia zones along stock margins and faults that host high-grade mineralization in the footwall of the Getchell Fault and Betze pit.

Cretaceous fluid evolution

Cretaceous fluids in the GT underwent a complex evolutionary process that can be traced using fluid inclusions, stable isotope data, and geologic relationships. An upper age limit is established by quartz veinlets containing one-phase liquid CH_4 inclusions that cut 109–103 Ma argillized rocks. Although these inclusions occur as both primary and secondary generations in the veinlets, one-phase liquid CH_4 inclusions were not identified in quartz veins that cut 97–92 Ma intrusions or younger mineralization [40]. Quartz veins in sedimentary rocks intruded by 97–92 Ma dacite and granodiorite

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

magmas host mixed CH_4–CO_2, one-phase CO_2, vapor-rich, and halite-bearing inclusions. Between ~103–95 Ma there was a change from CH_4-dominant organic fluids to a CH_4–CO_2 ± N_2 evolved magmatic fluid and finally, a less-evolved magmatic fluid represented by the assemblage of CO_2 ± CH_4 and N_2 with halite-bearing and vapor-rich inclusions [64](Figure 8). Mineralization during this time frame was dominated by pyrrhotite.

The emplacement and crystallization of the ~92 Ma Osgood Mountains granodiorite stock marked a significant compositional change to the hydrothermal system (Figure 8 and Figure 9). Early gas-rich (e.g., > 20 mol%) and CH_4-dominant fluids produced by metamorphic devolatilization were replaced by CO_2-dominant magmatic fluids with modest total-gas contents (e.g., ≤ 10 mol%) based on quadrupole mass spectrometer (QMS) analyses. There were also corresponding changes of pyrrhotite- to pyrite-dominant mineralization and initial δD values of –91.2 to –123‰ increased to –76‰ (Figure 9). The latter sample represents an Ag-rich quartz vein in the Osgood Mountains granodiorite stock.

This fluid evolution is not unique based on work by Chicharro et al. [66]. The intrusion of granite into organic-rich host rocks of the Central Iberian Zone, Spain caused metamorphism that produced assemblages of N_2–CH_4 and H_2O–N_2–CO_2–CH_4 fluid inclusions. A subsequent mixing of metamorphic and magmatic fluids caused immiscibility and the formation of a N_2-rich phase. However, fluid inclusions trapped a CO_2-rich gas phase when magmatically derived fluids dominated the hydrothermal system. An accompanying change in mineralization consisted of pyrrhotite- to pyrite-dominant with the addition of magmatic fluids.

At the GT, characteristics of mineralizing fluids that post-date the emplacement of the ~92 Ma Osgood Mountains granodiorite stock are based on data for two samples (Figure 8 and Figure 9). A mineralogically distinct tectonic breccia has a dark siliceous matrix containing abundant fine-grained anhedral pyrite and coarse arsenopyrite crystals (≤ 4 mm). This breccia displaces the skarn that formed adjacent to the stock and QMS data for quartz and arsenopyrite separates record total gas contents of ≤ 8 mol%, with CO_2 being the dominant gas phase. The mineralizing fluid was of meteoric origin based on a δD value of –154‰, whereas a δD value of –94.6‰ supports a final magmatic input for mineralization in the siliceous–pyritic matrix of a 75 Ma breccia pipe [64]. Gold assays for the two samples range from 0.4–3 ppm, but the siting of gold was not established.

These results establish the characteristics of fluids produced by metamorphism of organic-rich sedimentary units and the evolution of Cretaceous intrusive rocks at relatively shallow depths in the GT. The emplacement of intrusions and metamorphism occurred at ~4–6 Km based on a geobarometrically calculated pressure of 1.5 kb [67]; the presence of miarolitic cavities in porphyry dikes [18]; concordant K/Ar ages for hornblende and biotite from the Osgood Mountains stock and a nearby andesite dike [35,68]; and cooling of the stock to < 125°C within 2 m.y. of emplacement [3].

Eocene fluids sources

Getchell trend

The analytical data for fracture-controlled CT gold mineralization in the Getchell property are indicative of a magmatically derived fluid. Samples of Main ore-stage jasperoid containing auriferous pyrite

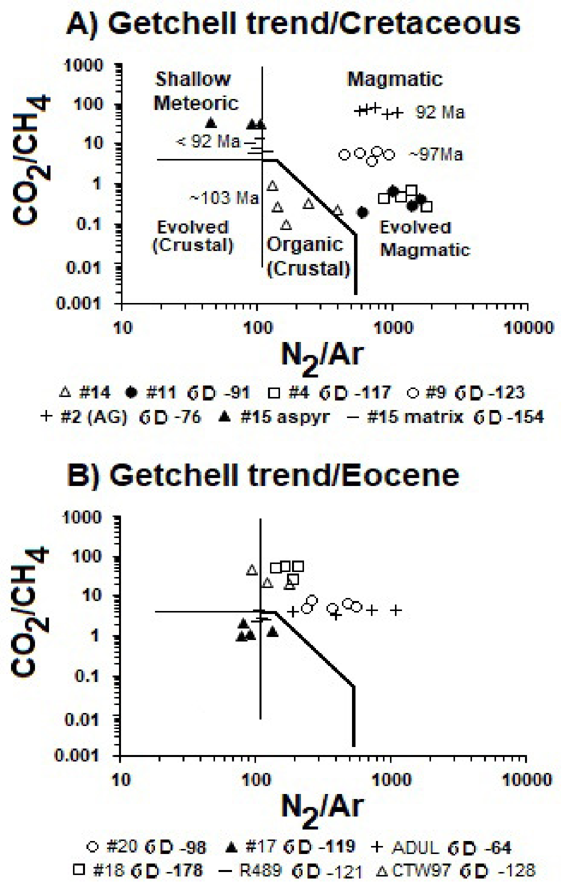

Figure 8: Plots of CO_2/CH_4 vs N_2/Ar and corresponding δD values for samples of A) Cretaceous quartz and arsenopyrite. Sample 11 is a gold-mineralized quartz vein; Sample 2 is a quartz vein in the Osgood Mountains stock containing 60 ppm Ag; and Sample 15 is a gold-mineralized breccia containing coarse-grained arsenopyrite. B) Gas data for samples of Main ore-stage jasperoid from the Getchell property and Twin Creeks mine. Sample ADUL is epithermal quartz from the DZ Fault and sample 18 (31 ppm Au) is proximal to the DZ Fault, Twin Creeks mine. The remaining sample numbers correspond to those in Groff [40] and Groff [39]. Abbreviations: AG = silver and aspyr = arsenopyrite.

have $\delta^{34}S$ values of 1–3‰ [69]; QMS gas data plot near the N_2 apex in a N_2–Ar–He ternary diagram (Figure 10); and δD values of –33‰ to –114‰ (Figure 11) [1,13] all support a magmatic source. Mineralization occurred as short-lived events based on nanoSIMS analyses of pyrite from the TRDG deposit that identified distinct pyrite textures and chemical zoning [30]. These discrete pulses of gold mineralization were associated with the periodic injection of a hot and gas-rich fluid having δD values > –60‰ and $\delta^{34}S$ values ≤ 3‰ (Figure 11 and Figure 12). Note that the highest gas concentrations are due to episodic boiling in NE-trending faults [9].

Although magmatically derived fluids dominated the hydrothermal system at the Getchell property, fluids that deposited stratabound Main ore-stage mineralization at the Twin Creeks mine underwent an evolution like in the Cretaceous igneous–hydrothermal event. Samples of auriferous jasperoid plot to form a trend that supports mixing between organic and metamorphic fluids (Figure 11). In contrast to the CH_4-rich Cretaceous fluids produced by metamorphic devolatilization, the Eocene organic and metamorphic fluids were N_2

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

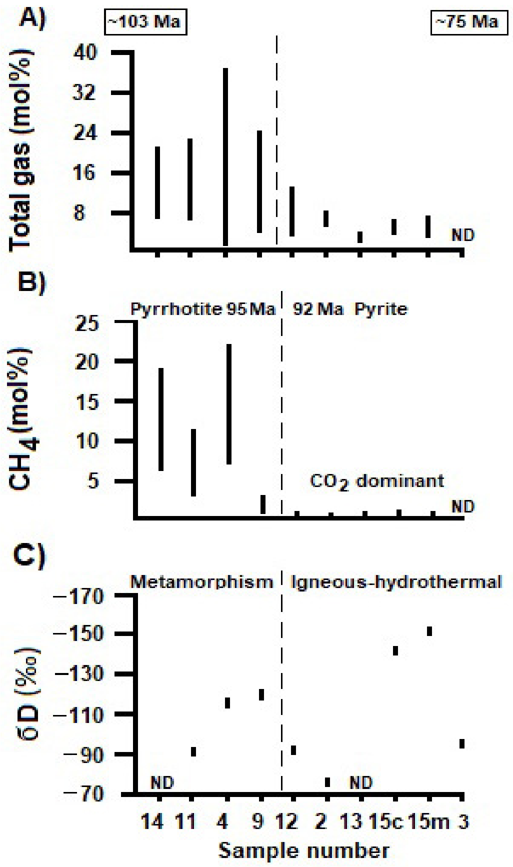

Figure 9: Summary diagram for Cretaceous hydrothermal events showing changes in fluid characteristics and mineralogy during the transition from metamorphism to igneous activity [64].

rich (e.g., ≤13.8 mol%). A change during the Eocene to a magmatic and CO_2-dominant hydrothermal system didn't occur until near the end of Main ore-stage, as recorded by structures containing kaolinite (δD = −78.9‰ to −89.5‰; [41]) and white crystalline quartz veins (δD = −93.6‰) that cut fine-grained massive jasperoid (δD = −178‰) hosting N_2-rich fluid inclusions [40].

However, residual organic and metamorphic fluids in the hydrothermal system are indicated by carbonaceous material occurring in growth bands of Late ore-stage orpiment [9]. The dominance of magmatically derived fluids at this point is demonstrated by samples of orpiment that have $\delta^{34}S$ values of 0.3‰, δD values of −88.5‰, and host CO_2-rich fluid inclusions [44].

An abrupt transition from CT mineralization to low-sulfidation epithermal gold (LSEG) mineralization occurred at the Twin Creeks mine. This is recorded by plateau ages of 41.9 ± 0.25 Ma (CT gold) and 42.11 ± 0.43 Ma (LSEG) for adularia intergrown with ore minerals in high-grade samples [2]. The LSEG mineralization is controlled by NE-trending faults and occurs as veins or quartz stockworks, which cut jasperoid ore. Fluid inclusions record boiling with $T_h \leq 300°C$ [9] and the O–H isotope data of a sample overlap the magmatic water box (Figure 11). Native gold, visible in some samples, occurs as both disseminations within quartz grains and crosscutting veinlets. However, QMS analyses indicate that the auriferous fluid contained < 2 mol% total gas (Figure 12). Both Eocene CT and LSEG mineralization occurred at depths of < 1 km [9].

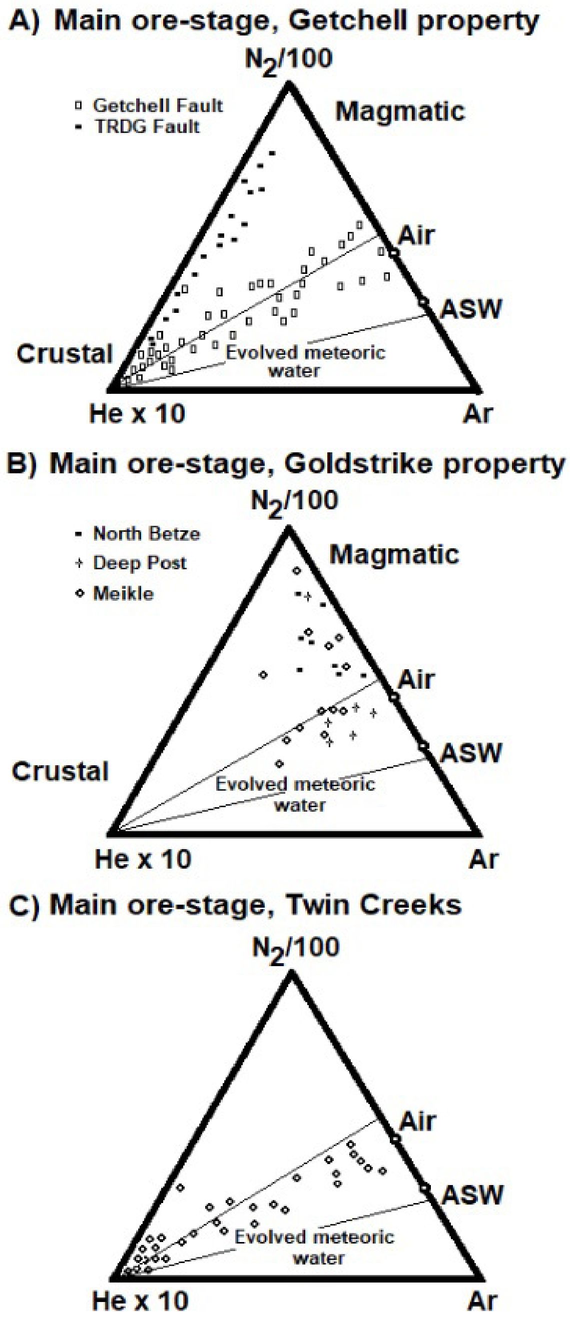

Figure 10: Ternary N_2–Ar–He ternary diagrams showing QMS gas data for Main ore-stage jasperoid samples from the A) Getchell property, B) Goldstrike property, and C) Twin Creeks mine [40].

Goldstrike property

Analytical data support CT gold mineralization being produced by magmatic and evolved meteoric waters. The best evidence of a magmatic source is provided by $\delta^{34}S$ values of ~0‰ for auriferous pyrite [51]; QMS gas data for high-grade silicified ore samples that plot near the N_2 apex in a N_2–Ar–He ternary diagram (Figure 10 [40]; and a change in $\delta^{18}O$ values outward from the Post Fault [70]. Whereas a significant component of meteoric water in the hydrothermal system that formed the Meikle deposit is based on Main ore-stage samples

Citation: Groff JA (2023) The Genesis of Carlin-Type Gold Deposits in Relation to the Geologic Evolution of Northern Nevada, USA. Int J Earth Environ Sci 8: 206 doi: https://doi.org/10.15344/2456-351X/2023/206

with δD = −135‰, $\delta^{18}O$ = −5‰ [54], and the distribution of QMS gas data in a N_2–Ar–He ternary diagram (Figure 10). A sedimentary source of sulfur for Meikle ore is also supported by samples of jasperoid and orpiment with $\delta^{34}S$ values of 9‰ and 5.3–5.8‰ [51,54], respectively, compared with $\delta^{34}S$ values of 0.3–2.2‰ for orpiment from the GT [9]. Fluid salinities of 0.2–4.5 wt.% NaCl equiv. for Late ore-stage minerals (e.g., calcite, realgar, and barite) at the GSP are also lower than values of ≤18 wt.% NaCl equiv. determined for the GT (Figure 12 [39,71]).

As ore fluids that formed the Meikle deposit were dominantly evolved meteoric water, an explanation is needed for the extreme amount of decalcification prior to mineralization. No magmatic fluid was identified by stable isotope data for minerals representing Main and Late ore-stage mineralization, including fine-grained clays in deep samples of altered igneous rocks [54]. However, QMS gas data for Main ore-stage samples do record a magmatic source (Figure 10). This could suggest that magmatic degassing produced a plume of CO_2, which mixed with meteoric water at shallow depths to generate an acidic solution. The source of CO_2 being subducted oceanic crust and overlying sediments, with additional carbon added by magma–wall rock interaction [72].

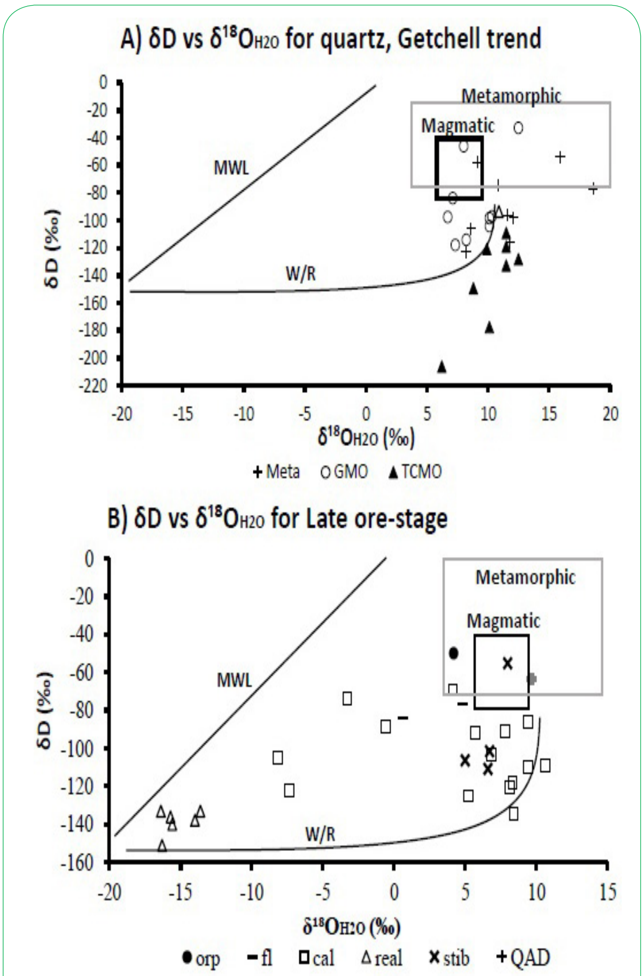

Figure 11: Plots of δD vs. $\delta^{18}O_{H2O}$ for A) metamorphic quartz and Main ore-stage jasperoid, Getchell trend and B) Late ore-stage minerals from the Getchell property and Twin Creeks mine. Note that stibnite-quartz pairs were analyzed to generate data for H–O isotopes. Abbreviations: Meta = metamorphic quartz, GMO = Getchell property Main ore-stage, TCMO = Twin Creeks Main ore-stage, orp = orpiment, fl = fluorite, cal = calcite, real = realgar, stib = stibnite, and QAD = epithermal quartz intergrown with adularia. Data are from Groff [41], Shigehiro [13], Cline and Hofstra [1](2000), Groff [9], and Groff [39].

At the GT, a CO_2-rich gas phase was produced by Cretaceous intrusions (Figure 8 and Figure 9) and a deep igneous source in the Eocene (Figure 11 and Figure 12). The periodic sealing of NE-trending faults in the Main pit, Getchell mine is indicated by episodic boiling that produced one- and three-phase CO_2 fluid inclusions in samples of Main and Late ore-stage minerals [1,9]. A sample of epithermal quartz from the NE-trending DZ fault at the Twin Creeks mine containing native gold and having a δD value of −64‰ also hosts fluid inclusions with a CO_2-dominant gas phase [9].

Ore Genesis

The brevity of CT gold mineralization in the GSP (≤ 40 k.y.; [73]) and Cortez Hills [5] shows how precursor events beginning in the Precambrian created ideal conditions for gold deposition. A primary

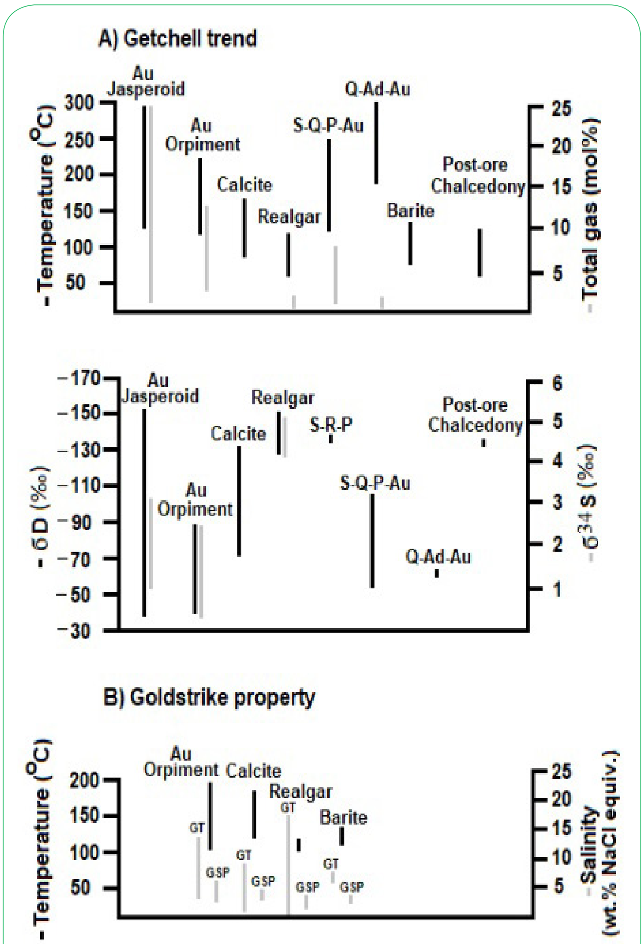

Figure 12: Summary diagram showing changes in temperature, salinity, total gas contents, and H–S isotopes for A) Main and Late ore-stage fluids in the Getchell trend and B) Late ore-stage fluids in the Goldstrike property. Abbreviations: S–R–P = barren stibnite–realgar–pyrite mineralization, S–Q–P–Au = stibnite–quartz–pyrite–gold mineralization, Q–Ad–Au = epithermal quartz–adularia–gold mineralization, GT = Getchell trend, and GSP = Goldstrike property. Data are from Groff [41], Groff [44], Groff [9], and Groff [64].

source of gold for the Nevada CT deposits was highly altered and metalliferous mantle rocks produced by subduction that began off the west coast of North America in the Triassic [12,23]. Melts generated from these fertile rocks, and associated metamorphism, supplied auriferous fluids that formed CT deposits. Evidence for this deep source of gold is best provided by geologic relationships and analytical data for the GT.

A distal location to any known center of Eocene igneous activity and limited amounts of meteoric water in the hydrothermal system, based on fluid salinities > 10 wt.% NaCl equiv. for both Main and Late ore-stage [9,1,13,39], served to preserve the characteristics of auriferous fluids. An important point is how Eocene and Cretaceous metamorphic fluids have distinct compositions that indicate different source areas. Deep-seated metamorphic fluids associated with the generation and ascent of Eocene magmas have a N_2-rich gas phase and depleted δD values (e.g., −207‰). Whereas Cretaceous metamorphism occurred at relatively shallow depths (e.g., ~4–6 Km) and generated a CH_4-rich fluid with δD values of −54‰ to −116‰ (Figure 9 and Figure 11). These data also plot differently in δD vs. $\delta^{18}O$ and CO_2/CH_4 vs. N_2/Ar diagrams (Figure 8 and Figure 11).

The Eocene metamorphic fluid was present during the formation of CT deposits in the Main pit, Getchell mine and GSP. Samples of Main ore-stage jasperoid from the N-trending Getchell Fault have QMS gas data that record N_2 gas concentrations of ≤ 7.5 mol% [41] and plot to form the same trend in a N_2–Ar–He ternary diagram as Main ore-stage samples from the Twin Creeks mine (Figure 10). There are also similarities in the QMS gas data for Main ore-stage samples from the GSP that include N_2 gas concentrations ≤ 6.9 mol% [40]. Secondly, when the QMS data for Main ore-stage samples from the Twin Creeks mine and GSP record total gas contents of ≥ 5 mol%, N_2 is the dominant gas phase (Figure 13). This N_2-rich gas phase was also identified in a sample of Late ore-stage orpiment from the Betze pit (Figure 14).

The derivation of auriferous fluids from a deep-seated magmatic source is supported by several lines of evidence. There is a glaring absence of Eocene igneous rocks in the GT, yet stable isotope and fluid inclusion data support a magmatic origin for auriferous fluids that had to come from a deep source. This is evident for siliceous ore, hosting CO_2-rich fluid inclusions, that occurs along high-angle faults at the Main pit and TRDG deposit. In a broader sense, the role of Eocene stocks and mineralization is clear for base metal–gold–silver deposits such as Fortitude [74] and McCoy–Cove [75], Battle Mountain–Eureka trend. This includes deep CT mineralization underlying the Cove deposit that was associated with a late phase of the Brown stock based on etching of base metal crystals by acidic ore fluids and changes in Au:Ag ratios relative to the stock [12]. These points suggest that giant CT deposits formed in association with the evolution of deep plutonic complexes, whereas a small CT deposit in a zoned mineralizing system was related to an individual stock now exposed at the surface.

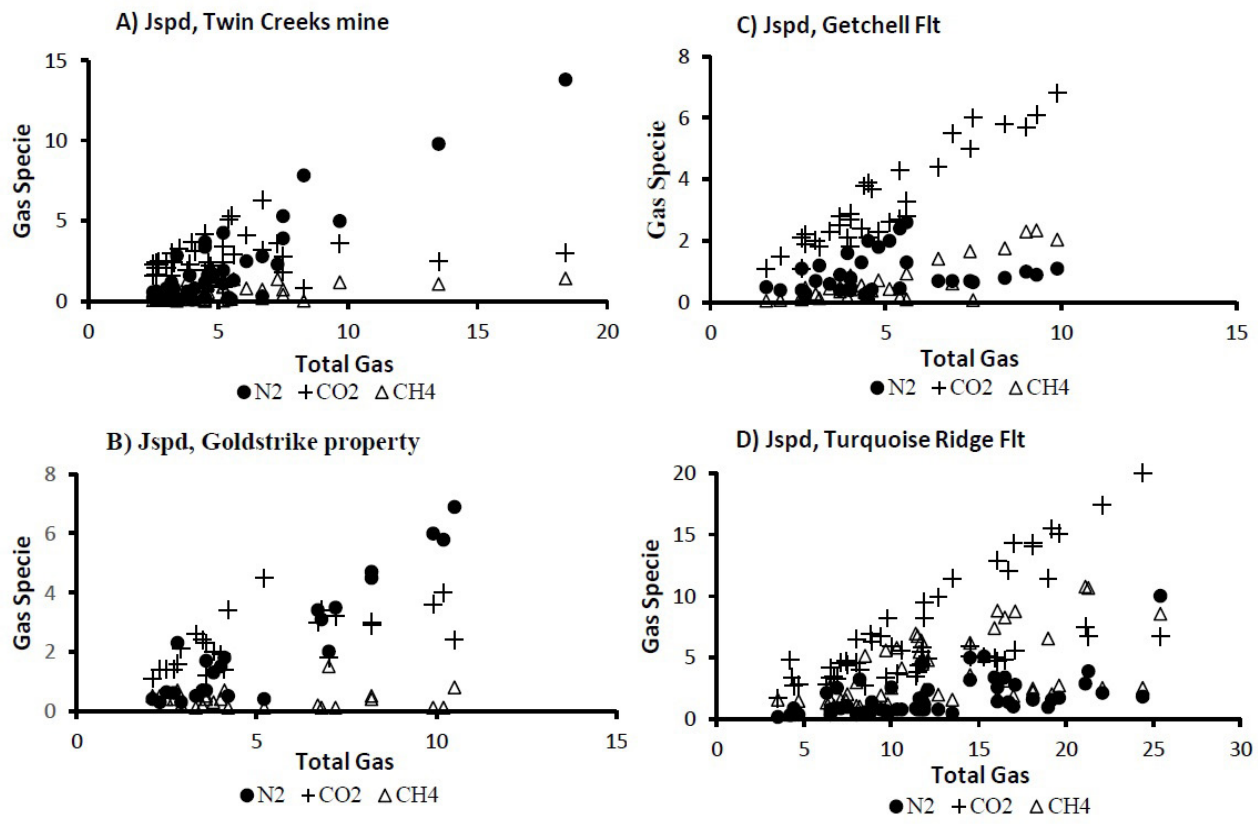

Figure 13: Plots showing the concentrations of N_2, CO_2, and CH_4 vs. total gas for samples of Main ore-stage jasperoid from A) the Twin Creeks mine, B) the Goldstrike property, C) the Getchell Fault, Getchell mine, and D) Turquoise Ridge Fault, Getchell mine. Data are from Groff [40].

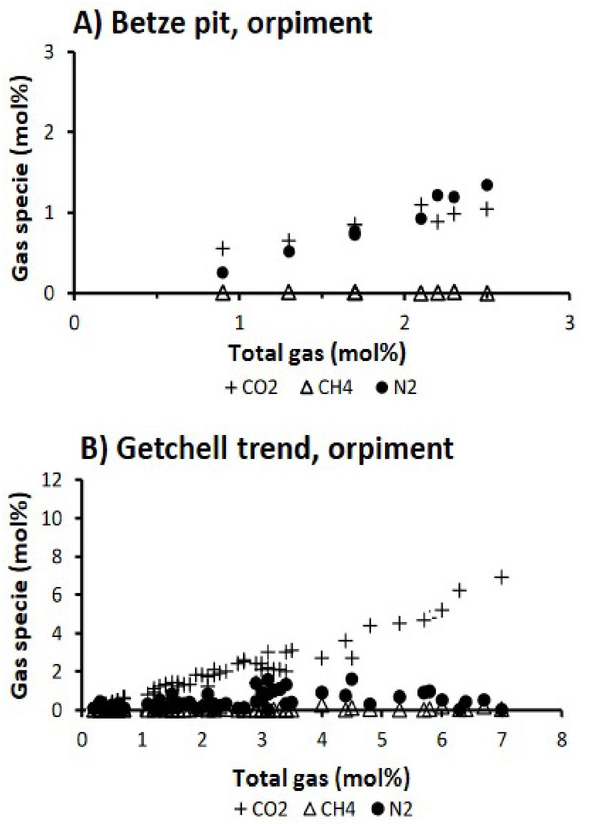

Figure 14: Plots showing the concentrations of N_2, CO_2, and CH_4 vs. total gas for samples of Late ore-stage orpiment from A) the Betze pit, Goldstrike property and B) the Getchell property and Twin Creeks mine. Data are from Groff [64]. Note that total gas concentrations > 10 mol% were excluded from graph A and the symbol for N_2 gas is an open circle in order to show greater detail.

The Carlin-style deposits with lesser gold endowments in Malaysia and Indonesia are also part of zoned mineralizing systems associated with singular stocks. Stable isotope data are indicative of a magmatic source for auriferous fluids, H_2S, and CO_2 [76,77]. Although these deposits formed near a craton margin in association with plate subduction and along regional structures, the source of auriferous fluids was a single stock. As a point source of heat and fluids at shallow depths, steep thermal gradients around a stock would create geochemical/mineralogical zoning. Whereas auriferous fluids evolved from a deep plutonic complex could rise rapidly along basement faults, or associated structures, to react with ferroan carbonates that were produced by older hydrothermal systems. A potentially important point is how porphyry intrusions were the mineralizing agents for Carlin-style deposits in Malaysia and Indonesia but were not the source of auriferous fluids in the GSP [52].

The above examples of intrusion-related Carlin-style deposits and a small CT orebody associated with the Brown stock, when combined with data for the GT support two important points. There is direct evidence that igneous rocks produced characteristic CT alteration and evolved auriferous fluids in addition to being the heat engine to drive fluid flow. Secondly, the giant CT deposits formed due to mineralization on a regional scale from auriferous fluids evolved during the crystallization of deep plutonic complexes.

A final point concerning the genesis of CT deposits involves the absence or presence of large volumes of meteoric water in the hydrothermal system. Limited amounts of meteoric water in Main ore-stage mineralization at the Getchell property are indicated by depleted $\delta^{18}O$ and $\delta^{13}C$ values only within or proximal to ore zones and fluid pathways [38,78]; saline Main and Late ore-stage fluids [13,64]; and QMS gas data for the TRDG deposit that indicate basinal and magmatic sources (Figure 10). In contrast, carbonate rocks have depleted $\delta^{18}O$ values at least 3-4 km from significant orebodies in the GSP [79] and hydrothermal fluids with a significant component of meteoric water were identified using QMS gas data (Figure 10).

The evolution of meteoric water to become an ore fluid by leaching a diverse suite of metals from host rocks [54,80] could account for mineralogical differences in CT ore in the GSP vs. GT. These include five types of oreshoots identified in the Betze pit [59,47,50], a greater diversity of minerals (e.g., base metals–rutile–Ag sulfosalts), and a more complex mineral paragenesis (Figure 4 and Figure 7). However, gold leached from country rocks would augment that introduced by an evolving plutonic complex derived from the melting of highly altered and mineralized mantle rocks above a subduction zone. The importance of these mantle rocks in ore genesis extends beyond CT deposits to Jurassic Au–polymetallic deposits [81], Cretaceous porphyry Cu–Mo deposits [82,83], Tertiary Au–polymetallic and porphyry copper deposits [75,84], and Miocene epithermal Au–Ag deposits [85].

Conclusion

Eocene CT deposits represent the culmination of a multiple-step process that began in the Precambrian. This includes rifting to create basement structures; soft sediment deformation during the deposition of rock units; thrusting to produce a regional structural trap; the formation of ferroan carbonates; subduction-related alteration and mineralization of mantle rocks; and important ground preparation caused by Mesozoic igneous events. Although there was considerable variation in the timing and underlying mechanisms for some of these precursor events, the combination of all was necessary to create ideal conditions for the rapid formation of giant CT deposits.

The sources of auriferous fluids include magmatic, metamorphic, and evolved meteoric waters. At the GT, magmatically derived fluids dominated the hydrothermal system for deposits in the Getchell property compared with organic–metamorphic fluids at the Twin Creeks mine. The different characteristics of Cretaceous and Eocene metamorphic fluids support a deep source for the latter. Whereas CT deposits in the GSP formed from fluids with magmatic, metamorphic, and meteoric sources. Gold was principally derived from highly altered and mineralized mantle rocks that were a source area for Eocene igneous rocks. Whereas large-scale circulation of fluids at the GSP leached gold from SEDEX mineralization and diagenetic pyrite to increase the endowment of these deposits.

Acknowledgments

The author would like to thank staff geologists at the different mines for help with collecting samples and their willingness to provide insights about the geology of these deposits. Furthermore, data interpretation was improved through discussion of stable isotope data with Dr. Andrew Campbell and quadrupole mass spectrometer gas data with the late Dr. David Norman.

Competing Interests

The authors declare that they have no competing interests.

References

1. Cline, J.S., Hofstra, A.H., 2000, Ore fluid evolution at the Getchell Carlin-type gold deposit, Nevada, USA: Eur. Journal of Mineralogy 12, 195–212.
2. Hofstra, A.H., Cline, J.S., 2000, Characteristics and models for Carlin- type gold deposits: Reviews in Econ. Geol. 13, 163–220.
3. Groff JA, Heizler MT, McIntosh WC, Norman DI 1997, $^{40}Ar/^{39}Ar$ dating and mineral paragenesis for Carlin-type gold deposits along the Getchell Trend. Econ Geol 92: 601–622.
4. Henry, C.D., Ressel, M.W., 2000 Eocene magmatism of northeastern Nevada: the smoking gun for Carlin-type gold deposits, in Cluer JK, Price JG, Struhsacker EM, Hardyman RF, Morris CL, eds., Geology and Ore Deposits 2000: The Great Basin and Beyond. Ren Geol Soc of Nevada, 365–388.
5. Henry, C.D., John, D.A., Leonardson, R.W., McIntosh, W.C., Heizler, M.T., Colgan, J.P., Watts, K.E., 2022, Timing of Rhyolite Intrusion and Carlin-Type Gold Mineralization at the Cortez Hills Carlin-Type Deposit, Nevada, USA: Econ. Geol. https://doi.org/10.5382/econgeo.4976.
6. Tretbar, D., 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 28, 947–950.
7. Hulen, J.B., Collister, J.W., 1999, The oil-bearing, Carlin-type gold deposits of Yankee Basin, Alligator Ridge District, Nevada. Economic Geology 1999;; 94 (7): 1029–1049. doi: https://doi.org/10.2113/gsecongeo.94.7.1029
8. Emsbo, P., 1999, Origin of the Meikle high grade gold deposit from the superposition of Late Devonian Sedex and mid-Tertiary Carlin-type gold mineralization: Unpub. PhD thesis, Golden, Colorado School of Mines, 394p.
9. Groff, J.A., 2019, Evidence of boiling and epithermal vein mineralization in Carlin-type deposits on the Getchell trend, Nevada: Ore Geology Reviews 106, 340–350.
10. Percival, T.J., Radtke, A.R., Bagby, W.C., 1990, Relationships among carbonate-replacement gold deposits, gold skarns, and intrusive rocks, Bau mining district, Sarawak, Malaysia: Mining Geology 40, 1–16.
11. Turner, S.J., Flindell, P.A., Hendri, D., Hardjana, I., Lauricella, P.F., Lindsay R.P., Marpaung, B., White, G.P., 1994, Sediment-hosted gold mineralization in the Ratatotok district, north Sulawesi, Indonesia: J. Geochem. Explor. 50, 317–336.
12. Muntean, J.L., Bonner, W., Hill, GT., 2017, Carlin-style gold mineralization at the Cove deposit in Nevada, USA: possible missing link between Carlin-type gold deposits and magmatic hydrothermal systems: Proceedings of the 14th Biennial Meeting of the Society for Geology Applied to Mineral Deposits, Quebec, 14, 71–74.
13. Shigehiro, M., 1999, Mineral paragenesis and ore fluids at the Turquoise Ridge Gold deposit, Nevada: Unpub. MS thesis, Las Vegas, Univ. of Nevada, 152p.
14. Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., Ahall, K.I., 1999. Refining Rodinia: Geologic evidence for the Australia-Western U.S. connection in the Proterozoic. GSA Today 9 (10), 1–7.
15. Timmons, J.M., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., Heizler, M.T., 2001, Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest- and north-trending tectonic grains in the southwestern United States: Geol. Soc. of America Bulletin 113, 163–190.
16. Muntean, J.L., Coward, M.P., Tarnocai, C.A., 2007, Paleozoic normal faults in north-central Nevada: Deep crustal conduits for Carlin-type gold deposits: Geol. Soc. Of London. Spec. Pub. 272, 571–587.
17. Stewart, J.H., Poole, F.G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran miogeocline, Great Basin, western United States: in Dickinson, W.R., ed., Tectonics and Sedimentation: Tulsa, Soc. Econ. Petrologists and Mineralogists, 27–57.
18. Hotz, P.E., Wilden, R., 1964, Geology and mineral deposits of the Osgood Mountains quadrangle, Humboldt County, Nevada: U.S.G.S. Prof. Paper 431, 128p.
19. Bloomstein, E.I., Massingill, G.L., Parratt, R.L., Peltonen, D.R., 1991. Discovery, Geology, Mineralization of the Rabbit Creek Gold Deposit, Humboldt County, Nevada: in Raines, G.L., Lisle, R.E., Schafer, R.W., Wilkinson, W.H., eds., Geology and Ore Deposits of the Great Basin. Geol. Soc. of Nevada, Reno, 821–843.
20. Thoreson, R.F., Jones, J.E., Breit, Jr., F.J., Doylwe-Kunkle, M.A., Clarke, L.J., 2000, The geology and gold mineralization of the Twin Creeks gold deposits, Humboldt County, Nevada: Soc. Econ. Geol. Guidebook Series 32, 175–187.
21. Cassinerio, M., Muntean, J., 2011, Patterns of lithology, structure, alteration and trace elements around high-grade ore zones at the Turquoise Ridge deposit, Getchell district, Nevada: in Steininger, R.C., Pennell, W.M., eds., Geol. Soc. of Nevada, Great Basin Evolution and Metallogeny: 2010 Symposium Proceedings, Reno, Nevada, 949–977.
22. Madden-McGuire, D.J., Marsh, S.P., 1991, Lower Paleozoic host rocks in the Getchell gold belt: several distinct allochthons or a sequence of continuous sedimentation?: Geology 19, 489–492.
23. Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M., Hickey, K.A., 2005. Carlin-type gold deposits in Nevada: Critical geologic characteristics and viable models. Econ. Geol. 100th Anniv. Vol, 451–484.
24. Roberts, R.J., 1966. Metallogenic Provinces and Mineral Belts in Nevada: Nevada Bureau of Mines Report 13, pt. A, 47–72.
25. Berger, B., Taylor, J., 1980, Pre Cenozoic normal faulting in the Osgood Mountains, Humboldt County, Nevada: Geology 8, 594–598.
26. Stenger, D.P., Kesler, S.E., Peltonen, D.R., Tapper, C.J., 1998, Deposition of gold in Carlin-type deposits: The role of sulfidation and decarbonation at Twin Creeks, Nevada: Econ. Geol. 93, 201–215.
27. Breit, F.J., Ressel, M.W., Anderson, S.D., Muirhead, E.M.M., 2005 Geology and gold deposits of the Twin Creeks mine Humboldt County, Nevada: Geol. Soc. of Nevada, Window to the World: Symposium Proceedings, Reno–Sparks, Nevada, 431–452.
28. Barber, K.M., 2015, Geology, alteration, geochemistry, and paragenesis of the Vista Vein shear zone deposit, Humboldt County, Nevada: Unpub. MS thesis, Reno, Univ. of Nevada, 98p.
29. Fortuna, J., Kesler, S.E., Stenger, D.P., 2003, Source of iron for sulfidation and gold deposition, Twin Creeks Carlin-type deposit, Nevada: Econ. Geol. 98, 1213–1224.
30. Barker, S.L.L., Hickey, K.A., Cline, J.S., Dipple, G.M., Kilburn, M.R., Vaughan, J.R., Longo, A.A., 2009, Uncloaking invisible gold: use of nanoSIMS to evaluate gold, trace elements, and sulfur isotopes in pyrite from Carlin-type deposits: Econ. Geol. 104, 897–904.
31. Eck, N.C., 2010, The effects of contact metamorphism on host rocks of Carlin-type mineralization at the Getchell development, Nevada, USA: Unpub. MS thesis, Reno, Univ. of Nevada, 112p.
32. Taylor, B.E., O'Neil, J.R., 1977. Stable isotope studies of metasomatized Ca–Fe–Al–Si skarns and associated metamorphic and igneous rocks, Osgood Mountains, Nevada: Contrib. Min. Petrol. 63, 1–49.
33. Fortuna, J., Kesler, S.E., Stenger, D.P., 2003, Source of iron for sulfidation and gold deposition, Twin Creeks Carlin-type deposit, Nevada: Econ. Geol. 98, 1213–1224.
34. Cail, T.L., Cline, J.S., 2001. Alteration associated with gold deposition at the Getchell Carlin-type gold deposit, north-central Nevada: Econ. Geol. 96, 1343–1359.
35. Silberman, M.L., Berger, B.R., Koski, R.A., 1974, K–Ar age relations of granodiorite emplacement and tungsten and gold mineralization near the Getchell mine, Humboldt County, Nevada: Econ. Geol. 69, 646–656.
36. Osterberg, M.W., Guilbert, J.M., 1991, Geology, wall-rock alteration, and new exploration techniques at the Chimney Creek sediment-hosted gold deposits, Humboldt County, Nevada: Geol. Soc. of Nevada, Geology and Ore Deposits of the American Cordillera: 1990 Symposium Proceedings, Reno–Sparks, Nevada, 805–819.
37. Hall, C.M., Kesler, S.E., Simon, G., Fortuna, J., 2000, Overlapping Cretaceous and Eocene alteration, Twin Creeks Carlin-type gold deposit, Nevada: Econ. Geol. 95, 1739–1752.
38. Cassinerio, M.D., 2010, Patterns of lithology, structure, alteration, trace elements, carbonate mineralogy, and stable isotopes around high grade Carlin-type deposits: Turquoise Ridge deposits, Getchell District, Nevada: Unpub. MS thesis, Reno, Univ. of Nevada, 230p.
39. Groff, J.A., 2021, Fluid evolution during Cretaceous and Eocene igneous–Hydrothermal events in the Getchell trend, Nevada: Ore Geology Reviews 137, 104303.
40. Groff, J.A., 2018 Distinguishing generations of quartz and a distinct gas signature of deep high-grade Carlin-type gold mineralization using quadrupole mass spectrometry. Ore Geology Reviews 95:518-536.
41. Groff, J.A., 1996. 40Ar/39Ar Geochronology of Gold Mineralization and Origin of Auriferous Fluids for the Getchell and Twin Creeks Mines, Humboldt County, Nevada: Unpub. PhD thesis, Socorro, New Mexico Institute of Mining and Technology, 291p.

42. Cline, J.S., 2001. The Timing of Gold and Arsenic Sulfide Mineral Deposition at the Getchell Carlin-Type Gold Deposit, North-Central Nevada: Econ. Geol. 96, 75–95.

43. Bloomstein, E.I., Massingill, G.L., Parratt, R.L., Peltonen, D.R., 1991. Discovery, Geology, Mineralization of the Rabbit Creek Gold Deposit, Humboldt County, Nevada: in Raines, G.L., Lisle, R.E., Schafer, R.W., Wilkinson, W.H., eds., Geology and Ore Deposits of the Great Basin. Geol. Soc. of Nevada, Reno, 821–843.

44. Groff, J.A., 2018b, Fluid mixing during late-stage Carlin-type mineralization in the Getchell and Twin Creeks deposits, Nevada: Ore Geology Reviews 101, 960–965.

45. Evans, J.G., 1980, Geology of the Rodeo Creek NE and Welches Canyon quadrangles, Eureka County, Nevada: U.S.G.S. Bulletin 1473, 81p.

46. Armstrong, A.K., Theodore, T.G., Kotlyar, B.B., Lauha, E.G., Griffin, G.L., Lorge, D.L., Abbott, E.W., 1997, Preliminary facies analysis of Devonian authochthonous rocks that host gold along the Carlin trend, Nevada: in Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., Parratt, R., eds., Carlin-type Gold Deposits Field Conference: Econ. Geol. Guidebook Series 28, 53–74.

47. Peters, S.G., Leonardson, R.W., Ferdock, G.C., Lauha, E.A., 1997, Breccia types in the Betze orebody, Goldstrike Mine, Eureka County, Nevada, in Vikre, Peter, Thompson, T.B., Bettles, K., Christensen, Odin, Parratt, R., eds., Carlin-type Gold Deposits Field Conference: Soc. Econ. Geol. Guidebook Series 28, 87–100.

48. Christensen, O.D., 1996, Carlin trend geologic overview, in Green, S.M., and Strusacker, E., eds., Geology and ore deposits of the American Cordillera Road Trip B, Structural Geology of the Carlin Trend: Geol. Soc. of Nevada Field Trip Guidebook Compendium, 1995, Reno/Sparks, Nevada, 147–156.

49. Resnell, R. 1990, An anticline trapping model for Carlin-type disseminated gold deposits, in Hausen, D.M., Halbe, D.N., Petersen, E.U., Tafuri, W.J., eds., Gold '90: Proceedings of the Gold 90 Symposium, Salt Lake City Utah, February 26 to March 1, 1990, 21–23.

50. Peters, S.G., 1996, Definition of the Carlin trend using orientation of fold axes and applications to ore control and zoning in the central Betze orebody, Betze-Post Mine: in Green, S.M., Struhsacker, E., eds., Geology and ore deposits of the American Cordillera, Trip Guide B–Structural Geology of the Carlin Trend: Geol. Soc. of Nevada Field Trip Guide Compendium, 1995, Reno/Sparks, NV, 203–239.

51. Kesler, S.E., Riciputi, L.C., Ye, N., 2005. Evidence for a magmatic origin for Carlin-type gold deposits: isotopic composition of sulfur in the Betze-post-screamer deposit, Nevada, USA: Mineral. Deposit. 40, 127–136. https://doi.org/10.1007/s00126-005- 0477-9.

52. Ressel, M.W., Noble, D.C., Heizler, M.T., Volk, J.A., Lamb, J.B., Park, D.E., Conrad, J.E., Mortensen, J.K., 2000, Gold-mineralized dikes at Griffin and Meikle: Bearing on the age and origin of deposits of the Carlin Trend, Nevada: in Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman R.F., Morris, C.L., eds., Geology and Ore Deposits 2000: the Great Basin and Beyond: Geological Society of Nevada Proceedings, May 15–18, 2000, 79–100.

53. Peters, S.G., Ferdock, G.C., Woitsekhowskaya, M.B., Leondarson, R., Rahn, J., 1998, Oreshoot zoning in the Carlin-type Betze orebody, Goldstrike mine, Eureka County, Nevada: U.S.G.S. Open-File Report 98–620, 59p.

54. Emsbo, P., Hofstra, A.H., Lauha, E.A., Griffin, G.L., 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: Econ. Geol. 98, 1069–1100.

55. Henry, C.D., Ressel, M.W., 2000, Eocene magmatism of northeastern Nevada: the smoking gun for Carlin-type gold deposits, in Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond: Reno, Geol. Soc. of Nevada, 365–388.

56. Leventhal, J., Hofstra, A., 1990, Characterization of carbon in sediment-hosted gold deposits, northcentral Nevada: in Hausen, D.M., Halbe, D.N., Petersen, E.U.,Tafuri, W.J., eds., Gold '90: Proceedings of the Gold 90 Symposium, Salt Lake City Utah, February 26 to March 1, 1990, 365–368.

57. Walck, C.M., 1989, Petrology and petrography of the metamorphic aureole associated with the Deep Post orebody, Eureka County, Nevada: Unpub. MS thesis, Rolla, Missouri School of Mines, 48p.

58. Arehart, G.B., Kesler, S.E., O'Neil, J.R., Foland, K.A., 1993, $^{40}Ar/^{39}Ar$, K/Ar, and fission-track geochronology of sediment-hosted disseminated gold deposits at Post-Betze, Carlin trend, NE Nevada: Econ. Geol. 88, 622–646.

59. Leonardson, R.W., Rahn, J.E., 1996, Geology of the Betze-Post gold deposits, Eureka County, Nevada: in Coyner, A.R., Fahey, eds., Geology and Ore Deposits of the American Cordillera: Geol. Soc. of Nevada, Symposium Proceedings, Reno/Sparks, Nevada, April,1995, 61–94.

60. Ferdock, G.C., Caster, S.B., Leonardson, R.W., Collins, T., 1997, Mineralogy and paragenesis of ore stage mineralization in the Betze gold deposit, Goldstrike mine, Eureka County, Nevada: in Vikre, Peter, Thompson, T.B., Bettles, K., Christensen, O., Parrat, R., eds., Carlin-type Gold Deposits Field Conference, Econ. Geol. Guidebook Series 28, 75–86.

61. Emsbo, P., Hofstra, A.H., 2000, Jurassic auriferous polymetallic mineralization at the Goldstrike mine, Carlin trend, Nevada: in Cluer, J.K., Price, J.G., Strusacker, E.M., Hardyman, R.F., Morris, C.L., eds., Geology and Ore Deposits: 2000 the Great Basin and Beyond: Geological Society of Nevada, Symposium Proceedings, May 15-18, 2000, B2.

62. Emsbo, P., Groves, D.I., Hofstra, A.H., Bierlein, F.P., 2006, The giant Carlin gold province: A protracted interplay of orogenic, basinal, and hydrothermal processes above a lithospheric boundary: Mineralium Deposita 41, 517–525.

63. M.W., Henry, C.D., 2006 Igneous Geology of the Carlin Trend, Nevada: Development of the Eocene Plutonic Complex and Significance for Carlin-Type Gold Deposits. Economic Geology 101: 347–383.

64. Groff, J.A., 2021, Fluid evolution during Cretaceous and Eocene igneous–Hydrothermal events in the Getchell trend, Nevada: Ore Geology Reviews 137, 104303.

65. Cassinerio, M., Muntean, J., 2011, Patterns of lithology, structure, alteration and trace elements around high-grade ore zones at the Turquoise Ridge deposit, Getchell district, Nevada: in Steininger, R.C., Pennell, W.M., eds., Geol. Soc. of Nevada, Great Basin Evolution and Metallogeny: 2010 Symposium Proceedings, Reno, Nevada, 949–977.

66. Chicharro, E., Boiron, M.C., Lopez-Garcia, J.A., Barfod, D.N., Villaseca, C., 2016. Origin, ore forming fluid evolution and timing of the Logrosan Sn–(W) ore deposits (Central Iberian Zone, Spain): Ore Geol. Revs. 72, 896–913.

67. Taylor, B.E., 1976, Origin and significance of C–O–H fluids in the formation of Ca–Fe–Si skarn, Osgood mountains, Humboldt County, Nevada: unpub. PhD thesis, Stanford, Stanford Univ., 284p.

68. Berger, B., Taylor, J., 1980, Pre Cenozoic normal faulting in the Osgood Mountains, Humboldt County, Nevada: Geology 8, 594–598.

69. Cline, J.S., Stuart, F.M., Hofstra, A.H., Premo, W., Riciputi, L., Tosdal, R.M., Tretbar, D.R., 2003, Multiple sources of ore-fluid components at the Getchell Carlin-type gold deposit, Nevada, USA: in Eliopoulos, D.G., ed., Mineral exploration and sustainable development. Millpress, Rotterdam, 965–968.

70. Lubben, J.D., Cline, J.S., Barker, S.L.L., 2012, Ore Fluid Properties and Sources from Quartz-Associated Gold at the Betze-Post Carlin-Type Gold Deposit, Nevada, United States: Econ. Geol. 107 1351–1385. https://doi.org/10.2113/econgeo.107.7.1351.

71. Groff, J.A., Campbell, A.R., Norman, D.I., 2002. An evaluation of fluid inclusion micro- thermometric data for orpiment–realgar–calcite–barite–gold mineralization at the Betze and Carlin mines. Nevada: Econ Geol. 97, 1341–1346.

72. Lowenstern, J.B., 2001, Carbon dioxide in magmas and implications for hydrothermal systems: Mineralium Deposits 36, 490–502. DOI 10.1007/s001260100185.

73. Hickey, K.A., Barker, L.L., Dipple, G.M., Arehart, G.B., Donelick, R.A., 2014. The brevity of hydrothermal fluid flow revealed by thermal halos around giant gold deposits: implications for Carlin-type gold systems: Econ. Geol. 109, 1461–1487.

74. Myers, G.L., Meinert, L.D., 1991, Alteration, mineralogy, and gold distribution in the Fortitude gold skarn: in Raines, G.L., Schafer, R.W., Wilkinson, W.H., eds, Geology and ore deposits of the Great Basin, Symposium proceedings, April 1990, Reno Nevada, 407–417.

75. Johnston, M.K., Thompson, T.B., Emmons, D.L., Jones, K., 2008. Geology of the Cove Mine, Lander County, Nevada and a Genetic Model for McCoy–Cove Hydrothermal System: Econ. Geol. 103, 759–782.

76. Hofstra, A.H., Christensen, O.D., 2000, Comparison of Carlin-type Au deposits in the United States, China, and Indonesia: Implications for genetic models and exploration: USGS Open File Rept. 02–13, 64–94.

77. Percival, T.J., Hofstra, A.H., Gibson, P.C., Noble, D.C., Radtke, A.S., Bagby, W.C., Pickthorn, W.J., Mckee, E.H., 2018, Sedimentary rock-hosted gold deposits related to epizonal intrusions, Bau district, island of Borneo, Sarawak, East Malaysia: Reviews in Econ. Geol. 20, 259–297.

78. Muntean, J.L., Cassinerio, M.D., Arehart, G.B., Cline, J.S., Longo, A.A., 2009. Fluid pathways at the Turquoise Ridge Carlin-type gold deposit, Getchell district, Nevada: Geol. Soc. Nevada Spec. Public. 49, 67–69.
79. Barker, S.L.L., Dipple, G.M., Hickey, K.A., Depore, W.A., Vaughnm J.R., 2013 Applying stable isotopes to mineral exploration: teaching an old dog new tricks: Econ. Geol. 108, 1–9.
80. Large, R.R., Bull, S.W., Maslennikov, 2011, A carbonaceous sedimentary source-rock model for Carlin-type gold deposits: Econ. Geol. 106, 331–358.
81. Nutt, C.J., Hofstra, A.H., 2007, Bald Mountain Gold Mining District, Nevada: A Jurassic Reduced Intrusion-Related Gold System: Econ. Geol. 102, 1129–1155.
82. Barton, M.D., 1990. Cretaceous Magmatism, Metamorphism, and Metallogeny in the East-Central Great Basin: Geol. Soc. Am. Memoir 174, 283–302.
83. McKee, E.H., 1992, Potassium argon and $^{40}Ar/^{39}Ar$ geochronology of selected plutons in the Buckingham area: in Theodore, T.G., Blake, D.W., Loucks, T.A., Johnson, C.A., eds., Geology of the Buckingham stockwork molybdenum deposit and surrounding area, Lander County, Nevada: U.S.G.S. Prof. Paper 798-D, p. 36–40.
84. Myers, G.L., Meinert, L.D., 1991, Alteration, mineralogy, and gold distribution in the Fortitude gold skarn: in Raines, G.L., Schafer, R.W., Wilkinson, W.H., eds, Geology and ore deposits of the Great Basin, Symposium proceedings, April 1990, Reno Nevada, 407–417.
85. John, D.A., Wallace, A.R., 2000, Epithermal gold–silver deposits related to the northern Nevada Rift: in Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman R.F., Morris, C.L., eds., Geology and Ore Deposits 2000: the Great Basin and Beyond: Geological Society of Nevada Proceedings, May 15–18, 2000, 155–175.