Lithogeochemistry of Carlin-type gold mineralization in the Gold Bar district, Battle Mountain-Eureka trend, Nevada

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Abstract

The Gold Bar district contains five Carlin-type gold deposits and four resources for a combined gold endowment of 1.6 M oz [50 t]. The gold deposits are hosted in Devonian carbonate rocks below parautochthonous and allochthonous Paleozoic siliciclastic rocks emplaced during the Early Mississippian Antler orogeny. The district is in the Battle Mountain-Eureka trend, a long-lived structural feature that localized intrusions and ore deposits of different types and ages.

The whole-rock geochemistry of four different mineralized and unmineralized Devonian carbonate rock units (two favorable and two unfavorable) were determined and interpreted in the context of the regional geology. A combination of basic statistics, R-mode factor analysis, isocron plots, and alteration diagrams were utilized to (1) identify favorable geochemical attributes of the host rocks, (2) characterize alteration and associated element enrichments and depletions, and (3) identify the mechanism of gold precipitation. This approach also led to the recognition of other types of alteration and mineralization in host rocks previously thought to be solely affected by Carlin-type mineralization.

Unit 2 of the Upper Member of the Denay Formation, with the highest Al\textsubscript{2}O\textsubscript{3}, Fe\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} contents and the lowest CaO content, is the most favorable host rock. Based on the high regression coefficients of data arrays on X–Y plots that project toward the origin, Al\textsubscript{2}O\textsubscript{3} and TiO\textsubscript{2} were immobile and K\textsubscript{2}O and Fe\textsubscript{2}O\textsubscript{3} were relatively immobile during alteration and mineralization. Specific element associations identified by factor analysis are also prominent on isocon diagrams that compare the composition of fresh and altered equivalents of the same rock units. The most prominent associations are: Au, As, Sb, SiO\textsubscript{2}, Tl, –CaO and –LOI, the main gold mineralizing event and related silicification and decalcification; Cd, Zn, Ag, P, Ni and Ti, an early base metal event; and MgO, early dolomitization. Alteration diagrams, consisting of X–Y plots of SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3}, K\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3}, CO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3}, [S/Al\textsubscript{2}O\textsubscript{3}]/[Fe\textsubscript{2}O\textsubscript{3}/Al\textsubscript{2}O\textsubscript{3}], provide evidence for progressive silicification, decarbonation (decalcification and dedolomitization), argillization (illite), and sulfidation as a function of gold mineralization. The latter process is identified as the principal mechanism of gold precipitation.

The lithogeochemistry of the ores in the Gold Bar district is typical of that documented in classic Carlin-type gold deposits in the region, but the size of the deposits and the intensity of alteration and mineralization are less. The presence of other types of mineralization in the Gold Bar district is also common to most of the other Carlin-type districts located in major mineral
1. Introduction

The Gold Bar district is comprised of five deposits (Gold Bar, Gold Pick, Gold Ridge, Goldstone and Gold Canyon) and four subeconomic resources (Mill Site, Pot Canyon, Cabin Creek and Hunter; Figs. 1 and 2). All are low-grade, bulk-mineable, sedimentary rock-hosted disseminated gold deposits that have been classified as “Carlin-type” (French et al., 1996). Most of the gold was produced from weathered oxidized ores by cyanide heap leach methods. Approximately 485,200 ounces of gold were recovered from the deposits (Cope and Arbonies, 1998) and the district is estimated to contain a total gold resource of approximately 1.6 M oz [50 t] (French et al., 1996). The geology, gold mineralization and wall-rock alteration in the Gold Bar deposit have been described by Broili et al. (1988), Masinter (1990) and French et al. (1996). The district is located in the southern Roberts Mountains approximately 48 km northwest of Eureka, NV. It is in the southern portion of the Battle Mountain-Eureka trend (Fig. 1) (Roberts, 1966), a 200-km-long, northwest-trending structural zone that contains a variety of ore deposits. These include: barite deposits (Papke, 1984), pluton-related base and precious metal deposits of Jurassic, Cretaceous, and middle Tertiary age, Carlin-type gold deposits of middle Tertiary age, and volcanic-hosted low-sulfidation gold–silver deposits of Late Tertiary age (Maher et al., 1993; Fig. 1).

The purpose of this paper is to characterize the whole-rock geochemistry of mineralized and unmineralized Devonian lower plate carbonate rocks in the Gold Bar district to constrain an ore depositional model. This study also provides information on mass transfer of constituents related to alteration and mineralization, and emphasizes the importance of host rock composition for ore deposition in Carlin-type systems. These aspects were studied because host rock composition is known to be an important control on gold mineralization in Carlin-type deposits (Hofstra and Cline, 2000). Specifically, sulfidation of ferroan minerals in the host rocks has been recognized by other studies in other districts to be the principal mechanism of gold deposition (Hofstra et al., 1991; Hofstra, 1994; Stenger et al., 1998; Emsbo, 1999; Hofstra and Cline, 2000; Cail and Cline, 2001). Thus, thin bedded to laminated, silty limestones with ferroan calcite or dolomite are often the most favorable host rocks in Carlin-type systems. The results presented in this study facilitate comparisons of Gold Bar with other Carlin-type deposits in Nevada and other parts of the world and the approaches used can aid interpretation of geochemical data obtained from other deposits.

This paper is part of a larger study that combines results of detailed geologic and structural mapping with geochemistry and structural analyses to determine the spatial and temporal relations between structures and gold mineralization in the Gold Bar district and to develop an exploration model for the deposits that is applicable to other areas of similar geologic setting (Yigit, 2001). The nature of the structures associated with gold mineralization and their possible origins are discussed from deposit to district scale by Yigit and Nelson (2000) and Yigit et al. (in press). Jasperoids associated with structures and gold mineralization are classified and characterized in terms of texture, petrography, stable isotope composition and lithogeochemistry in Yigit et al. (in preparation).

2. Geologic setting

The geology of the Gold Bar district is characterized by two Paleozoic assemblages separated by the Roberts Mountains thrust (RMT; Merriam and...
Anderson, 1942) and intervening parautochthonous rocks (Murphy et al., 1984). These assemblages were juxtaposed by shortening during the Late Devonian to Early Mississippian Antler orogeny (Roberts, 1949, 1951; Johnson and Pendergast, 1981; Speed and Sleep, 1982). The allochthonous upper plate consists of siliciclastic rocks and minor carbonate rocks of the western assemblage, and the autochthonous lower plate consists of a thick section of limestone and dolomite of the eastern assemblage (Fig. 2). The parautochthonous rocks were deposited in a foreland basin east of the leading edge of the Roberts Mountains thrust and consist of interbedded silty arenite, wacke and chert-quartz arenites of the Webb Formation (Murphy et al., 1984; Martin, 1985). The western assemblage is characterized by deep marine sedimentary rocks of the Vinini Formation (Finney and Perry, 1991; Finney et al., 1993). Eastern assemblage rocks include, from oldest to youngest; Roberts Mountains
Fig. 2. Regional geology of the Gold Bar district from this study with data from Murphy et al. (1978); Atlas Precious Metals, 1983–1996; Cordex Exploration, 1995–1996; Barrick Gold Exploration, 1997–1998.
Formation, Lone Mountain Formation, Nevada Group and Devils Gate Formation (Merriam and Anderson, 1942; Nolan et al., 1956; Johnson, 1962, 1966; Roberts et al., 1967; Johnson and Kendall, 1976; Johnson et al., 1978; Murphy et al., 1978; McKee et al., 1986). The Nevada Group is represented by the Denay and McColley Canyon Formations. The Denay Formation is divided into Lower and Upper Members, and the Upper Member consists of, from oldest to youngest, Unit 1, Unit 2 and Unit 3 (Fig. 3). Local exposures of the Permian Garden Valley Formation, consisting of coarse clastic rocks, unconformably overlie the RMT, and constitute an overlap assemblage (Roberts, 1949, 1951; Roberts et al., 1967). Volcanic rocks of Tertiary age ranging from rhyolite to basalt (Maher et al., 1993) unconformably overlie the Paleozoic rocks (Fig. 2).

The Gold Bar district can be divided into three major structural zones that are separated by the high-angle Range Front fault and Wall fault zones. Dominantly allochthonous rocks and the overlap assemblage are exposed by the Range Front fault in the southwestern Roberts Mountains. Allochthonous, autochthonous and parautochthonous rocks are exposed in the Wall fault zone (Fig. 2).

The primary controls on gold mineralization in the district are structural, especially high-angle faults, and lithologic, especially Unit 2 of the Upper Member of the Denay Formation and the Bartine Member of the McColley Canyon Formation. The Bartine Member of the McColley Canyon Formation hosts gold mineralization at Gold Pick, Gold Ridge, Cabin Creek and Hunter deposits. Unit 2 of the Upper Member of the Denay Formation hosts gold mineralization at Gold Bar, Goldstone, Gold Canyon, Pot Canyon, and Mill Site deposits (Fig. 3). Gold mineralization in the Gold Bar district is closely associated with decalcification and to a lesser extent with silicification along high-angle faults (Broili et al., 1988; Masinter, 1990; French et al., 1996). More intensely decalcified zones in the gold deposits correlate well with high-grade ore.

Hofstra (1995) and Hofstra et al. (1999) showed that most Carlin-type deposits formed between 42 and 30 Ma, are coextensive with a 34–43 Ma belt of calc-alkaline igneous rocks, and formed soon after the onset of extension in the region. They proposed that the deposits formed along major structures in the upflow zone of convection cells that developed in response to the high heat flow and increased permeability in this setting. Henry and Boden (1998) and Henry and Ressel (2000) propose that Eocene magmatic centers provided the heat for the hydrothermal systems and emphasize that porphyry dikes and magnetic anomalies are present in or near many districts.

In the Gold Bar district, however, there is an absence of dikes and other geologic or geophysical evidence for a magmatic center. Furthermore, only meteoric water has been detected by hydrogen isotope studies (Hofstra et al., 1999) and sulfur isotopic data suggest that reduced sulfur was derived from sedimentary rocks (Yigit et al., in preparation). Even though the Gold Bar deposit is overlain by rhyolitic welded tuffs dated at 24.70 ± 0.06 Ma (Yigit et al., in preparation), the absence of gold-related alteration in these volcanic rocks suggests a post-mineral age for volcanism (Yigit and Nelson, 2000) consistent with the Late Eocene age constraints on Carlin-type deposits throughout the region and the model proposed by Hofstra et al. (1999). The closest igneous centers include the 34 Ma old East Summit Dome located ~ 13 km northeast, the 34 Ma Roberts Creek volcanic center located ~ 8 km north and the 36 Ma Mount Hope rhyolite porphyry intrusion and related molybdenum deposit 17 km east (Roberts et al., 1967; Maher et al., 1993). The nearest Carlin-type gold deposits (Fig. 1) are Chert Cliff, ~ 16 km northeast (Vikre and Maher, 1996) and Tonkin Springs ~ 16 km north (Espell and Rich, 1991; Maher et al., 1993) that is located on the northern extension of the Wall fault zone.

There is evidence in the district for minor Late Devonian mineralization related to basinal brines similar to that documented in the Carlin trend (Emsbo et al., 1999). Black shales in the Denay Formation are locally metalliferous (see below). Two small barite deposits, Bat and Bar, were mined from the Devils Gate and Vinini Formations in the northern Roberts Mountains (McKee et al., 1986). Barite mineralization consists of bedded barite (McKee et al., 1986) and barite–calcite ± sulfide veins. A few replacement Zn–Pb–Ag deposits and prospects are present in the northwestern Roberts
Mountains, such as Kelley Mine and Jackass prospect (Roberts et al., 1967; McKee et al., 1986), that may be related to concealed Mesozoic or Cenozoic intrusions or to older basinal brines. At least two stages of dolomitization have been observed in the lower plate carbonate rocks in the district. The early
stage is characterized by regional diagenetic dolomite that formed in a marine-phreatic mixing zone (Murphy and Dunham, 1977; Hoffmann, 1991). The late stage is characterized by sparry hydrothermal dolomite that is locally brecciated and contains up to 1.4% zinc, such as in the Wall fault zone.
3. Stratigraphy and petrology of lower plate carbonate rocks

Descriptions of stratigraphy are based on 2 years detailed geological and structural mapping in the district combined with measured sections and petrographic observations. Detailed descriptions of stratigraphy and petrography are provided in Yigit (2001).

The Silurian Lone Mountain Formation (Hague, 1892; Merriam, 1940), the stratigraphically lowest formation exposed in the Gold Bar district, consists of dense, light-gray to white, saccharoidal, thick-bedded to massive dolomite. The formation has a gradational contact with the underlying Roberts Mountains Formation and interfingers laterally and vertically with limestone of the Roberts Mountains Formation. Although a section measured in the Roberts Mountains is 670 m thick (Merriam and Anderson, 1942), its thickness is highly variable. The formation is at least 300 m or more in thickness in the Gold Bar district. The Lone Mountain Formation represents a dolomitized reef facies limestone.

The Devonian McColley Formation (Carlisle et al., 1957; Johnson, 1962) is divided into three members (Murphy and Gronberg, 1970), in ascending order: the Kobeh, Bartine and Coils Creek Members. The formation was deposited in a shallow water marine environment. The Kobeh Member conformably over-
lies the Lone Mountain Formation and is approximately 30 m thick in the Gold Bar district. The lower part of the member is dolomitic with silicified fossil debris, and weathers brownish gray to light gray. The upper part is a medium to light gray dolomitic mudstone and wackstone. The Kobeh Member is less resistant to erosion than the underlying Lone Mountain Formation, and is more resistant to erosion than overlying the Bartine Member.

The Bartine Member conformably overlies the Kobeh Member and consists of thin to medium-bedded, fossiliferous wackstone and packstone. The member is 75 to 115 m thick and contains abundant brachiopod shells that weather free from the matrix.

![Box and whisker plots of whole-rock lithogeochemical data showing difference in range for major element oxides in unmineralized lower plate carbonate rocks in the Gold Bar District, including from youngest to oldest Ddg: Devonian Devils Gate Formation, Dud3 –2 – 1: Unit 3 to 1 of the Devonian Upper Member of the Denay Formation, Dld: Devonian Lower Member of the Denay Formation. N= 23 (Ddg: 6, Dud3: 5, Dud2: 5, Dud1: 5, and Dld: 2).](image-url)
Atrypa and Eurekaspirifer brachiopods and Favosites tabulate corals are common fossils in the member (French et al., 1996).

The Coils Creek Member conformably overlies the Bartine Member, and is unconformably overlain by the Lower Member of the Denay Formation. It is medium gray and locally fossiliferous, and consists of medium to thick-bedded wackstone and packstone. The member varies from 30 to 60 m in thickness.

The Devonian Denay Formation (Johnson, 1966) is divided into Upper and Lower members (Murphy and Dunham, 1977). The Upper Member is subdivided into 3 units, which are, from oldest to youngest, Unit 1, Unit 2 and Unit 3 (French et al., 1996). The Lower Member of the Denay Formation is an approximately 120-m-thick monotonous sequence of thin to medium-bedded, medium to dark gray lime mudstone and wackstone. It has very distinct undulating bedding surfaces and contains minor microfossils. Microscopically it consists of well-sorted, homogenous micrite with sparry calcite veinlets without lamination. Based upon combined reagent staining (alizarin red S with potassium ferricyanide; Hitzman, 1999), it consists mostly of calcite with low iron content. The homogenous, well-sorted, micritic nature of the member and low fossil content is consistent with deposition in a relatively deep, quiet-water environment and thus represents a basinal facies.

Table 1
Element associations determined by seven-factor model for lower plate carbonate rock data from Gold Bar district

<table>
<thead>
<tr>
<th>Element</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
<th>Factor 7</th>
<th>Communalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (ppm)</td>
<td>0.025</td>
<td>0.013</td>
<td>0.922</td>
<td>0.013</td>
<td>0.016</td>
<td>0.013</td>
<td>0.854</td>
<td></td>
</tr>
<tr>
<td>Ag (ppm)</td>
<td>0.150</td>
<td>0.793</td>
<td>0.116</td>
<td>0.056</td>
<td>0.169</td>
<td>0.128</td>
<td>0.317</td>
<td>0.813</td>
</tr>
<tr>
<td>Sb (ppm)</td>
<td>-0.026</td>
<td>0.055</td>
<td>0.727</td>
<td>0.010</td>
<td>0.641</td>
<td>0.044</td>
<td>0.026</td>
<td>0.945</td>
</tr>
<tr>
<td>As (ppm)</td>
<td>0.161</td>
<td>-0.012</td>
<td>0.907</td>
<td>0.008</td>
<td>0.109</td>
<td>0.040</td>
<td>-0.012</td>
<td>0.863</td>
</tr>
<tr>
<td>Hg (ppm)</td>
<td>0.213</td>
<td>0.037</td>
<td>0.387</td>
<td>0.755</td>
<td>0.040</td>
<td>0.078</td>
<td>0.288</td>
<td>0.857</td>
</tr>
<tr>
<td>Ba (ppm)</td>
<td>0.297</td>
<td>0.019</td>
<td>0.004</td>
<td>0.829</td>
<td>0.149</td>
<td>0.126</td>
<td>0.013</td>
<td>0.814</td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>0.944</td>
<td>0.047</td>
<td>-0.015</td>
<td>0.158</td>
<td>0.001</td>
<td>0.082</td>
<td>0.088</td>
<td>0.934</td>
</tr>
<tr>
<td>Cd (ppm)</td>
<td>-0.088</td>
<td>0.969</td>
<td>0.002</td>
<td>0.062</td>
<td>-0.007</td>
<td>-0.021</td>
<td>0.001</td>
<td>0.951</td>
</tr>
<tr>
<td>Cr (ppm)</td>
<td>0.198</td>
<td>0.175</td>
<td>0.523</td>
<td>0.287</td>
<td>-0.038</td>
<td>0.029</td>
<td>0.590</td>
<td>0.776</td>
</tr>
<tr>
<td>Co (ppm)</td>
<td>0.745</td>
<td>-0.009</td>
<td>-0.102</td>
<td>0.455</td>
<td>-0.056</td>
<td>0.247</td>
<td>0.054</td>
<td>0.840</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>0.893</td>
<td>0.151</td>
<td>-0.011</td>
<td>0.298</td>
<td>-0.024</td>
<td>0.072</td>
<td>0.054</td>
<td>0.919</td>
</tr>
<tr>
<td>Ga (ppm)</td>
<td>0.778</td>
<td>0.243</td>
<td>0.181</td>
<td>0.236</td>
<td>0.307</td>
<td>-0.109</td>
<td>0.118</td>
<td>0.873</td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>0.151</td>
<td>0.084</td>
<td>0.001</td>
<td>0.777</td>
<td>0.388</td>
<td>0.053</td>
<td>0.019</td>
<td>0.786</td>
</tr>
<tr>
<td>Mn (ppm)</td>
<td>0.676</td>
<td>0.135</td>
<td>-0.015</td>
<td>0.299</td>
<td>0.069</td>
<td>-0.016</td>
<td>0.108</td>
<td>0.582</td>
</tr>
<tr>
<td>Mo (ppm)</td>
<td>0.519</td>
<td>0.139</td>
<td>0.002</td>
<td>0.003</td>
<td>-0.073</td>
<td>0.701</td>
<td>0.023</td>
<td>0.787</td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>0.565</td>
<td>0.698</td>
<td>-0.044</td>
<td>0.257</td>
<td>0.069</td>
<td>0.307</td>
<td>-0.016</td>
<td>0.974</td>
</tr>
<tr>
<td>P (ppm)</td>
<td>0.437</td>
<td>0.748</td>
<td>-0.097</td>
<td>0.093</td>
<td>0.284</td>
<td>0.030</td>
<td>0.051</td>
<td>0.853</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>0.102</td>
<td>-0.123</td>
<td>0.007</td>
<td>-0.181</td>
<td>-0.226</td>
<td>-0.425</td>
<td>-0.479</td>
<td>0.519</td>
</tr>
<tr>
<td>Ti (ppm)</td>
<td>0.215</td>
<td>0.658</td>
<td>0.515</td>
<td>-0.065</td>
<td>0.018</td>
<td>-0.079</td>
<td>0.202</td>
<td>0.796</td>
</tr>
<tr>
<td>W (ppm)</td>
<td>-0.010</td>
<td>0.072</td>
<td>0.058</td>
<td>0.142</td>
<td>0.923</td>
<td>0.055</td>
<td>-0.085</td>
<td>0.891</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>0.144</td>
<td>0.062</td>
<td>-0.142</td>
<td>0.784</td>
<td>0.148</td>
<td>0.303</td>
<td>-0.152</td>
<td>0.797</td>
</tr>
<tr>
<td>V (ppm)</td>
<td>0.405</td>
<td>0.453</td>
<td>0.050</td>
<td>0.604</td>
<td>0.286</td>
<td>0.040</td>
<td>0.102</td>
<td>0.829</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>0.033</td>
<td>0.949</td>
<td>-0.018</td>
<td>0.184</td>
<td>0.062</td>
<td>0.051</td>
<td>-0.011</td>
<td>0.943</td>
</tr>
<tr>
<td>Al2O3 (%)</td>
<td>0.986</td>
<td>0.019</td>
<td>0.087</td>
<td>0.069</td>
<td>-0.041</td>
<td>-0.017</td>
<td>0.017</td>
<td>0.978</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>-0.652</td>
<td>-0.091</td>
<td>-0.356</td>
<td>-0.136</td>
<td>0.120</td>
<td>-0.037</td>
<td>-0.597</td>
<td>0.951</td>
</tr>
<tr>
<td>Fe2O3 (%)</td>
<td>0.953</td>
<td>0.029</td>
<td>0.042</td>
<td>0.118</td>
<td>0.188</td>
<td>-0.005</td>
<td>0.056</td>
<td>0.963</td>
</tr>
<tr>
<td>K2O (%)</td>
<td>0.966</td>
<td>0.020</td>
<td>0.109</td>
<td>0.105</td>
<td>-0.051</td>
<td>0.062</td>
<td>0.093</td>
<td>0.971</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>0.347</td>
<td>0.181</td>
<td>-0.002</td>
<td>-0.100</td>
<td>-0.067</td>
<td>0.096</td>
<td>0.796</td>
<td>0.810</td>
</tr>
<tr>
<td>Na2O (%)</td>
<td>0.386</td>
<td>-0.083</td>
<td>-0.167</td>
<td>-0.243</td>
<td>0.225</td>
<td>-0.354</td>
<td>0.300</td>
<td>0.508</td>
</tr>
<tr>
<td>SiO2 (%)</td>
<td>0.568</td>
<td>-0.013</td>
<td>0.624</td>
<td>0.301</td>
<td>-0.161</td>
<td>-0.035</td>
<td>0.341</td>
<td>0.947</td>
</tr>
<tr>
<td>TiO2 (%)</td>
<td>0.978</td>
<td>0.018</td>
<td>0.088</td>
<td>0.102</td>
<td>-0.026</td>
<td>0.034</td>
<td>0.085</td>
<td>0.984</td>
</tr>
<tr>
<td>LOI (%)</td>
<td>-0.730</td>
<td>0.037</td>
<td>-0.537</td>
<td>-0.281</td>
<td>0.104</td>
<td>0.020</td>
<td>-0.194</td>
<td>0.950</td>
</tr>
<tr>
<td>Total (%)</td>
<td>-0.008</td>
<td>0.137</td>
<td>0.039</td>
<td>-0.045</td>
<td>-0.244</td>
<td>-0.681</td>
<td>-0.205</td>
<td>0.587</td>
</tr>
</tbody>
</table>

Extraction: principal components; Rotation: varimax raw, N=43.
Unit 1 of the Upper Member of the Denay Formation unconformably overlies the Lower Member, and consists of a 40- to 60-m-thick, medium to dark gray, medium- to thick-bedded, fossiliferous grainstone with subordinate packstone, wackstone, and recrystallized limestone. Fossiliferous coarse grainstones are very common at the base of the unit. Staining indicates that carbonates are mostly calcite. The unit appears to represent a shallow-water, reefal-slope facies.

Unit 2 of the Upper Member of the Denay Formation is represented by a sequence of laminated, thin-bedded, non-fossiliferous, locally carbonaceous lime mudstone, wackstone and local packstone. The unit varies from 6 to 36 m in thickness in the northeast portion of the district and reaches up to 120 m in the Gold Bar deposit. It is medium to dark gray to black in the unaltered outcrops and cream to buff colored in weathered outcrops. In thin sections, fenestral porosity, filled by calcite in some places, is the most common porosity type in the unit. Locally, it also contains ferroan calcite. Unit 2 is interpreted to have been deposited in a deep-water, oxygen-depleted, low-energy environment.

Unit 3 consists of approximately 75 m of interbedded, medium- to thick-bedded, oolitic and peloidal grainstones and packstones. It has a gradational contact with the overlying Devils Gate Formation. The upper stratigraphic level of the unit is generally coarser grained and highly fossiliferous. Microscopically, grainstones are mostly well rounded and well sorted within a sparry matrix. Most of the grainstones are peloidal without internal structures. The unit was probably deposited in a shallow-water, reef-slope environment.

The Middle to Late Devonian Devils Gate Formation (Merriam, 1940) consists of massive, cliff forming, light to medium gray, bioclastic packstones, wackstones and boundstone with minor grainstones and local dolomite. Due to structural complications, the true thickness of the formation is not known in the district. It is at least 30 m thick. In thin section, well-rounded and poorly sorted grains in the grainstone within a light color sparry matrix show flattening due to compaction. Some of the dolomitic samples with sugary texture have xenotopic dolomitic texture. The Devils Gate Limestone is interpreted to represent a carbonate reef facies.

4. Methods

To characterize the lithogeochemistry of lower plate carbonate rocks, 43 whole-rock samples were collected and analyzed for major, minor, and trace elements. Sample locations are provided in Yigit (2001). Unmineralized samples were collected from the Devils Gate, Denay (including Lower Denay and Unit 1, Unit 2, Unit 3) and McCollery Canyon formations in the Wall fault area, and mineralized samples were collected from the Gold Bar, Goldstone, Gold Pick and Gold Ridge deposits (Fig. 2). Whole-rock analyses were done by Chemex Laboratories using Fire Assay–Atomic Absorption (FA-AA) for gold and silver, metabolite fusion -XRF (X-Ray Fluorescence) for 11 major elements reported as oxides, and Inductively Coupled Plasma Spectrometer-Mass Spectrometer (ICP-MS) for 32 trace elements. Samples with values less than their respective analytical detection limits were assigned a value of half the analytical detection limit, and samples with values higher than their upper detection limits were assigned a value of 10% more than the upper detection limit for computation of data statistics. Statistica software was used in this study (StatSoft, 1995). Preliminary data statistics were studied to remove elements with insufficient variance and duplicates prior to computing population statistics. Where a component was determined as both the element and

| Table 2 Composition of factors in the seven-factor model solution for mineralized and unmineralized lower plate carbonate rock data from Gold Bar district |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Factor 1        | Factor 2        | Factor 3        | Factor 4        | Factor 5        | Factor 6        | Factor 7        |
| Al_2O_3         | Cd              | Au              | Ba              | W               | Mo              | MgO             |
| TiO_2           | Zn              | As              | Pb              | Sb              |                 |                 |
| K_2O            | Ag              | Sb              | Hg              |                 |                 |                 |
| Fe_2O_3         | P               | SiO_2           | U               |                 |                 |                 |
| Bi              | Ni              | Ti              | V               |                 |                 |                 |
| Cu              | Ti              | – CaO           |                 |                 |                 |                 |
| Ga              | – LOI           |                 |                 |                 |                 |                 |
| Co              |                 |                 |                 |                 |                 |                 |
| % Total variance for each factor | 37.7 | 12.6 | 11.0 | 9.0 | 5.8 | 4.9 | 3.5 |

Major contributing elements and major element oxides to each factor are listed in the order of decreasing factor loadings. Extraction: principal components; Rotation: varimax raw, N=43.
oxide, the higher quality form of the data was selected. Logarithmic (base 10) values of the data were used in the calculations of interelement correlations to decrease the range of data. Box and whisker plots were prepared to compare the range of the data from lithological subsets, and scatter plots were constructed to serve as a check on the linearity of the data, an assumption that underlies the standard correlation coefficient computations. Select samples of barren and mineralized strata were used to construct isocon diagrams. We also utilize another lithogeochemical data set for 30 mineralized and unmineralized samples.

Fig. 6. (A) Regression coefficients of Al₂O₃, TiO₂, K₂O and Fe₂O₃ for samples from the Gold Bar pit. (B) Scatter plots of Al₂O₃, TiO₂, K₂O and Fe₂O₃ showing that they are relatively immobile. (C) Plot of TiO₂ versus Al₂O₃ indicates that they are the most immobile pair, regardless of the alteration and mineralization. Constructed from data in Masinter (1990).
from the Gold Bar pit produced by Masinter (1990) to construct an isocon diagram and characterize compositional changes due to alteration.

5. Lithogeochemistry

Box and whisker plots of data from unmineralized samples from the Lower Member of Denay Formation, Unit 1, Unit 2, Unit 3 of the Upper Member of the Denay Formation and the Devils Gate Formation indicate that lower plate carbonate rocks have different arsenic, barium, manganese, phosphate, strontium and zinc contents (Fig. 4). Unit 2 has the highest arsenic, manganese, phosphate and strontium contents, and Unit 3 has the highest zinc content. In addition, unmineralized lower plate rocks also vary in Al₂O₃, CaO, Fe₂O₃, MgO and SiO₂ contents (Fig. 5). Unit 2 has the highest Al₂O₃, Fe₂O₃ and SiO₂ contents and the lowest CaO contents, and is one of the most favorable host-rocks for gold mineralization in the district. The Devils Gate limestone has the highest CaO content (clean limestone) and is rarely mineralized. Unit 3 and Unit 1 have the highest MgO contents due to the presence of dolomite but generally are not mineralized.

Correlation coefficients and scatter plots of the minor elements and major element oxides from 43 mineralized and unmineralized samples indicate that gold is positively correlated with silver, antimony, arsenic, mercury, barium, thallium and SiO₂. Gold is negatively correlated with CaO and Loss On Ignition (LOI, proxy for CO₂). Decrease in CaO and LOI are considered to indicate decalcification.

Together, these relationships suggest that decalcification of limestone or dolomitic limestone with low iron contents results in the creation of porosity, but little sulfidation. In contrast, decalcification of
Unit 2 limestones with high iron contents creates porosity and promotes sulfidation and gold deposition. The high Al$_2$O$_3$ and SiO$_2$ contents of Unit 2 limestones suggest that they also may be preferentially mineralized because they contain more siliciclastic detritus, resulting in greater permeability or reactivity.

5.1. Factor analysis

R-mode factor analysis was employed to identify element associations in the whole-rock sample data set, because it is able to reduce the number of initial variables to a fewer number of combined associations, or factors, based their mutual linear correlation coefficients. A seven factor model was selected because it accounts for a significant portion of the total data variation (84.5%), as quantified by eigenvalues, and it explains most of the variation in each element, as quantified by communalities (Table 1). The seven-factor model (Table 1) also is considered to be an appropriate solution because it has meaningful geologic and geochemical metal associations (Closs and Nichol, 1975). The relative contribution of an element to each factor is quantified by the loading value. Major contributing elements and major element oxides to each factor are represented in Table 2 in the order of decreasing factor loadings, along with the percent total variance for each factor. The intensity of a particular element association in a sample is quantified by the factor score and these data are available in Yigit (2001).

This model was developed using 43 samples that have 33 variables. Garratt (1993) has raised concern about the stability of statistical models where the number of the samples used is less than three times the number of variables. To test the stability of this factor model (Table 2), additional factor models were computed using fewer variables (26 and 24). Similar geologically meaningful factor associations were
obtained from these models. This suggests that the initial solution is stable.

Each of the seven factors can be interpreted to reflect lithologic variations and different types of alteration and mineralization in the lower plate carbonate rocks. Factor 1, with high loadings for Al₂O₃, TiO₂, K₂O, Fe₂O₃, Bi, Cu, Ga, and Co, may represent detrital components of carbonate rocks and is commonly associated with Unit 2 of the Upper Member of the Denay Formation. Factor 2, composed of high loadings for Cd, Zn, Ag, P, Ni, and Tl, may be a metalliferous black shale signature or an early base metal event characterized by zinc mineralization. Phosphate in Factor 2 could be related to early phosphate nodules. Factor 3, consisting of Au, As, Sb, SiO₂, Tl, –CaO and –LOI, represents the main gold mineralizing event and related alteration, silicification and decalcification of the rocks. Factor 3 is typical of those obtained from Carlin-type deposits in other districts (Hofstra and Cline, 2000). Factor 4, with high loading of Ba, Pb, Hg, U, and V is interpreted as mineralization associated with barite deposition. Factor 5 with W and Sb and Factor 6 with Mo may reflect distal porphyry molybdenum style mineralization or enrichment in black shale. Finally, Factor 7, dominated by high MgO, represents early diagenetic or hydrothermal dolomitization of limestones. The diverse element associations in the factor model suggest that the lower plate rocks in the district may have experienced a variety of mineralizing events that are not obvious in the field. Alternatively, some of the factors may represent different zones within one or more large hydrothermal systems. Detailed petrographic study of samples with high scores for each factor is needed to evaluate and refine this interpretation.

5.2. Immobile elements

Identification of immobile elements is important because they can be used to assess gains and losses of other elements due to alteration and mineralization.
(Gresens, 1967; Grant, 1986). Immobile, chemically incompatible elements maintain constant interelement ratios during alteration and mineralization and are easily identified on $X-Y$ plots because they lie along a common regression line that passes through the origin (Grant, 1986). The slope of the regression line is a function of the initial ratio of the two immobile elements in the unaltered rock. The most immobile pair of elements has the highest regression coefficients. Addition of components to the rocks, such as silica during silicification, dilutes the concentration of immobile elements, and subtraction of components from the rocks, such as CaO during decalcification, concentrates them (Fig. 6).

In addition to our data set, Masinter's (1990) 30-sample whole-rock data set from the Gold Bar deposit, consisting of mineralized and unmineralized samples, is used for mass transfer and alteration studies. Most of the samples are taken from Unit 2, and some samples are taken from Unit 1 of the Upper Member of the Denay Formation. Detailed petrographic descriptions of the samples are presented in Masinter (1990). Statistical analysis of the data indicates that $\text{Al}_2\text{O}_3$ and $\text{TiO}_2$, with highest regression coefficient (0.997), are the most immobile pair in the system (Fig. 6A and B). $\text{K}_2\text{O}$ and $\text{Fe}_2\text{O}_3$ are also relatively immobile in the system (0.734) (Fig. 6A and B). The lack of scatter in the plot of $\text{TiO}_2$ and $\text{Al}_2\text{O}_3$ indicates that the Al–Ti ratios are very uniform, regardless of alteration and mineralization (Fig. 6C). Fig. 6C also shows that different gold grades do not affect the slope of the regression line.

5.3. Isocon diagrams

Grant (1986) demonstrated that isocon diagrams can be used to calculate gain or loss of major, minor and trace elements due to alteration. This graphical method is based on Gresens' (1967) equations. Logarithmic isocon diagrams have proved useful in studies of mass transfer in Carlin-type systems (Hofstra, 1994; Hofstra and Cline, 2000) and are used here. The isocon is a line defined by the immobile elements that is parallel to the line of constant mass. An isocon that

![Fig. 9. Logarithmic isocon diagram showing mass flux associated with alteration in Unit 3 of the Upper Member of the Denay Formation. $N=7$ (averages of two altered and five unaltered samples).](image-url)
lies above the constant mass line indicates that alteration is related to mass loss, in which case, the concentrations of immobile elements in the altered rocks increase relative to the unaltered rock by the loss of other components.

In Fig. 7, altered samples from zones of intense decalcification and clay recrystallization (DCR-3) are plotted against unaltered samples (DCR-0) of Unit 2 argillaceous micrites from the Upper Member of the Denay Formation in the Gold Bar deposit (Masinter, 1990). The position of the isocon defined by immobile Al₂O₃ and TiO₂ indicates that decalcification caused mass losses of 44% to 51%. The logarithmic isocon diagram shows that Au, Hg, Zn, Sb, As and organic C are strongly enriched, whereas Ag, Tl, Pb, Cu, Ba and SiO₂ have modest gains. CaO, CO₂, MnO and LOI (proxy for CO₂) are constituents displaying the greatest losses. Al₂O₃, TiO₂, P₂O₅, K₂O, MgO, Na₂O, Cr, S, Te and total iron as Fe₂O₃ were all relatively immobile.

The strong losses of CaO indicate that carbonate dissolution was the major process accompanying gold mineralization in these samples. The lack of MgO enrichment indicates that there is no major dolomitization associated with gold mineralization. Silica replacement (jasperoid formation) was very minor in the decalcified zone of the Gold Bar deposit. The absence of S introduction in the altered samples is due partly to variations in the initial S content of Unit 2, but mainly to S depletions associated with weathering and oxidation of pyrite in the altered samples (as evident in Fig. 14, below). With the exception of Zn and organic C, the assemblage of strongly introduced and depleted components corresponds well with those (Au, As, Sb, SiO₂, Tl, –CaO and –LOI) that have strong loadings in Factor 3. The Zn in the altered samples was therefore introduced by another mineralizing event(s), likely during the pre-ore history of the rock. Organic C was not determined in the data set used for factor analysis, hence its relation to Factor 3 is uncertain.

Figs. 8–10 display isocon diagrams for rock suites analyzed in this study from the Devils Gate Formation, Unit 3 of the Upper Member of the Denay Formation in the Bartine Member of the McColley Canyon Formation (Mb). N=4 (one altered and average of three unaltered samples).

![Fig. 10. Logarithmic isocon diagram showing mass flux associated with alteration in the Bartine Member of the McColley Canyon Formation (Mb). N=4 (one altered and average of three unaltered samples).](image-url)
Formation, and the Bartine Member of the McColley Canyon Formation, respectively. The altered samples of Devils Gate Formation and Unit 3 exhibit only weak decalcification, silicification or Fe-oxide staining along fractures and are similar to those typically collected from surface exposures for exploration purposes. The altered samples of Bartine Member were collected from the walls of the mined out Gold Pick and Gold Ridge deposits.

The isocon diagrams for these units do not show contrasts as great as those in Unit 2 of the Upper Member of the Denay Formation (Fig. 7), and the element enrichments and depletions are much more variable. Some of this variability is due to inhomogeneities in the host rock compositions. However, the assemblages of enriched elements suggest that some of the variability is due to the effects of two or more mineralizing events. The near absence of CaO depletions and the enrichments of SiO₂ and MgO in altered samples from each of these stratigraphic units suggest that alteration consisted mainly of silicification and dolomitization. This is unlike the alteration in the Gold Bar pit where dolomitization is absent. In the Devils Gate Formation (Fig. 8), this type of alteration was accompanied by enrichments of Fe, P, Zn, and a wide variety of other base metals and trace elements with minor Au. In Unit 3 (Fig. 9), this alteration was accompanied by strong enrichments of Zn, P, Cd, Ag, and Au, with lesser enrichments of base metals and trace elements similar to those present in the Devils Gate. In the Bartine Member (Fig. 10), this alteration was accompanied by subtle CaO depletion and strong enrichments of Ba, P, Au, As, Sb, Hg, and a variety of base metals. In comparison to altered samples from Unit 3 and the Devils Gate Formation, Au grades, Au/Ag ratios, and As concentrations are higher in the

Fig. 11. CO₂ versus CaO alteration plot of different ore grades showing principal data arrays (gray) for the Gold Bar deposit, total of 30 samples mostly from Unit 2, and some samples from Unit 1 of Upper Member of the Denay Formation. Dol: Dolomitization, + Cal: Calcification, – Cal: decalcification, D: dissolution, Si: silicification, Ls: limestone. Constructed from data in Masinter (1990); data template from Hofstra and Cline (2000).
Bartine Member, suggesting it was more strongly affected by the Carlin system.

5.4. Alteration diagrams

Hofstra and Cline (2000) showed that X–Y plots of major components in the main alteration assemblages of Carlin-type systems could be used to characterize the initial rock composition and progressive changes due to silicification, decarbonation (decalcification and dedolomitization), argillization and sulfidation. In addition, correlation between the degree of alteration and gold grade can be presented and evaluated on these diagrams. Major-element oxide data from the Gold Bar deposit are used in the X–Y plots. Masinter’s (1990) 30-sample whole-rock data set is predominantly from Unit 2 with a few samples from Unit 1 of the Upper Member of the Denay Formation. Detailed sample descriptions are presented in Masinter (1990). Data templates for the plots are from Hofstra and Cline (2000). Although Masinter (1990) plotted the data differently, he arrived at similar conclusions to those presented here. The trends of the data arrays for Gold Bar on these plots are similar to those from Jerritt Canyon (Hofstra and Cline, 2000).

The CO₂ versus CaO plot shows the proportion of calcite, dolomite and other minerals (mostly silicate and sulfides) in the rocks. The shaded ellipse encompasses samples deemed by Masinter (1990) to be representative of unaltered Unit 2 argillaceous micritic limestone that hosts most of the gold. The carbonate fraction of these samples consists of approximately 75% calcite and 25% dolomite while the noncarbonate fraction consists predominantly of quartz and clays (Fig. 11). The alteration path (gray) on the CO₂ versus

![Image of SiO₂ versus Al₂O₃ alteration plot](image-url)

Fig. 12. SiO₂ versus Al₂O₃ alteration plot of different ore grades showing principal data arrays (gray) for the Gold Bar deposit, total of 30 samples mostly from Unit 2, and some samples from Unit 1 of Upper Member of the Denay Formation. C: carbonation, A: argillization, Ser: sericitization. Constructed from data in Masinter (1990); data template from Hofstra and Cline (2000).
CaO plot indicates that decalcification of argillaceous micritic limestone was followed by dissolution of dolomite and accompanied by silicification until all of the carbonate was removed (Fig. 11). In Fig. 11, at least 12 samples are clustered at the origin (quartz and clays), evidence of intense silicification characterized by jasperoid formation. The spread in the position of the relatively unmineralized samples (less than 0.1 ppm gold) on this diagram is due in part to initial lithologic differences (e.g. argillaceous micrite, fossiliferous limestone) and demonstrates that alteration is often not accompanied by gold mineralization.

The SiO₂ versus Al₂O₃ plot shows the proportion of quartz, phyllosilicates (muscovite and kaolinite), and other minerals (carbonate and sulfides) in the rock. As above, the shaded ellipse encompasses samples deemed by Masinter (1990) to be representative of unaltered Unit 2 argillaceous micritic limestone. The data for the samples from the Gold Bar pit indicate that decarbonation was accompanied by progressive silicification, characterized by jasperoid formation, until 98% of the limestone was replaced by silica (Fig. 12). However, some samples follow the silicification arrow towards pure quartz without significant dissolution.

The K₂O versus Al₂O₃ plot can be used to estimate the proportion of the white K-mica (muscovite, illite), kaolinite and other minerals (quartz, carbonate and sulfides) in the rock. The data for limestone from the Gold Bar pit indicate that muscovite or illite are the principal phyllosilicates in the altered samples and that there are minor amounts of kaolinite and smectite in the system (Fig. 13). Whole-rock infrared spectroscopy of the samples from Gold Bar pit indicated that illite-group clays are present in decalcified samples and smectite group clays are present in unaltered wall-
rock samples (Masinter, 1990). The pattern of data points that move towards and away from the origin provides evidence for both silicification and decalcification, respectively (Fig. 13).

The S/Al$_2$O$_3$ versus Fe$_2$O$_3$/Al$_2$O$_3$ plot can be very useful to measure the degree of sulfidation and to distinguish mechanisms of pyrite precipitation (Hofstra and Cline, 2000). Pyrite that forms by sulfidation of host rock iron has a vertical trajectory, whereas pyrite that forms by other mechanisms lies along a trajectory with a slope of 0.8. For reference, approximately 40% of the iron in normal marine shales deposited in oxygenated seawater is sulfidized due to production of H$_2$S by sulfate reducing bacteria (Raiswell et al., 1988). In anoxic or euxinic environments, the percentage of pyrite iron is even higher. Thus, the majority of the samples that plot below the 25% line have lost S due to weathering and oxidation of pyrite. The spread in the oxidized samples along the x-axis is due to Fe mobility, which results in depletions and enrichments in different samples (Fig. 14). Data from the few unoxidized samples plot above the 50% line and extend vertically up to the pyrite line, indicating a sulfidation process without significant addition of iron (Fig. 14). Two barren unoxidized samples plot outside the sulfidation zone and contain up to 15% introduced pyrite that Masinter (1990) interpreted to be diagenetic.

6. Conclusions

Unit 2 of the Upper Member of the Denay Formation is the one of the most favorable host rocks in the Gold Bar district. Lithogeochemical studies show that Unit 2 has the highest Al$_2$O$_3$, Fe$_2$O$_3$ and SiO$_2$ contents and the lowest CaO content, indicating that impure carbonates are preferentially mineralized. A seven-factor R-mode factor model suggests that the main episode of gold mineralization was characterized
by increases in Au, As, Sb, SiO₂, Tl, and decreases in CaO and LOI (volatiles). The negative loadings for CaO and LOI reflect decalcification, whereas the positive loading for SiO₂ reflects silicification associated with the main stage of gold deposition. The element associations indicated by the other factors provide evidence for additional types of unrelated alteration (e.g. dolomitization) and mineralization (mainly Zn and other base metals) that are not easily recognized in the field.

Statistical analysis of the data from the Gold Bar deposit indicates that Al₂O₃ and TiO₂ are the most immobile element pair in the system, as suggested by their high regression coefficient. Therefore, this pair is useful for mass transfer studies, especially calculation of mass losses related to alteration. K₂O and Fe₂O₃ are also relatively immobile in the system.

Mass transfer studies using logarithmic isocon diagrams suggest that decalcification caused mass losses of 44% to 51% in Unit 2 of the Upper Member of the Denay Formation. In Unit 2, Au, Hg, Zn, Sb, As and organic C are strongly enriched; whereas CaO, CO₂, MnO and LOI are strongly depleted. The introduction of Zn in Unit 2 is interpreted to be due to the superposition of Carlin-type mineralization on earlier Zn mineralization. Isocon diagrams for three other stratigraphic units provide evidence for silicification and dolomitization associated with base metal and P enrichments that are distinct from, and locally overprinted by, Carlin-type mineralization.

The alteration diagrams, CO₂ versus CaO and SiO₂ versus Al₂O₃, indicate that decarbonation (decalcification and dedolomitization) was accompanied by progressive silification, characterized by jasperoid formation. The K₂O versus Al₂O₃ plot suggests that illite-group clays are the principal phyllosilicates related to alteration and mineralization. The S/Al₂O₃ versus Fe₂O₃/Al₂O₃ plot indicates that pyrite has been completely destroyed in the oxidized samples, and the unoxidized samples suggest that sulfidation was the main gold precipitating process in the Gold Bar deposit.

The lithogeochemistry of the ores in the Gold Bar district is typical of that documented in other Carlin-type gold deposits in the region, but the size of the deposits and the intensity of alteration and mineralization are less. The presence of other types of mineralization in the district is also typical of the mineral belts in which Carlin-type deposits occur, showing long and complex histories. It is possible that superposition of mineralizing events may have played a role in gold mineralization at Gold Bar by creating favorable host rocks, but detailed mineral paragenesis, mineral composition, and stable isotopic studies of unoxidized ores and adjacent host rocks are required to establish this. This study shows that the application of basic statistics, factor analysis, isocon, and alteration diagrams to data from barren and variably mineralized rocks is a powerful approach for the interpretation of multi-element geochemical data in areas with complex histories and is of practical use for the development of genetic and exploration models. Especially during the initial stages of exploration major element data are often available and the method used in this paper can be easily applied. This can establish a model and help in the determination of favorable host rocks and alteration assemblages associated with Carlin-type gold mineralization.

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References


