Potential for Alkaline Igneous Rock-Related Gold Deposits in the Colorado Plateau Laccolithic Centers

By Felix E. Mutschler,1 Edwin E. Larson,2 and Michael L. Ross3

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ABSTRACT

Several types of productive gold deposits in the Rocky Mountains, ranging in age from 79 Ma to 26 Ma, show a close spatial, temporal, and genetic association with alkaline igneous rocks. Deposit types range from porphyry copper–precious metal systems characterized by Cu>Ag>Au or platinum-group elements, through transitional types, to epithermal precious-metal-only deposits commonly characterized by Au>Ag. The alkaline rocks associated with these deposits represent mantle melts which fractionated in crustal-level magma chambers. Coeval calc-alkaline igneous rocks formed by crustal melting and magma mixing occur with the alkaline rocks at many localities.
The igneous rocks of the Colorado Plateau laccolithic centers fall into two age groups: early Laramide (=72–70 Ma) and middle Tertiary (33–23 Ma). Calc-alkaline diorite porphyries are the most voluminous igneous rocks in these centers. Essentially coeval alkaline syenite porphyries occur at Mount Pennell in the Henry Mountains, the North and Middle Mountain centers in the La Sal Mountains, and the Navajo Mountain center. Small volumes of late-stage peralkaline granite and rhyolite are also present at the Mount Pennell and North Mountain centers. The rock chemistry and alteration-mineralization assemblages of the Colorado Plateau laccolithic centers were compared to those of productive Rocky Mountain alkaline rock-related gold deposits. This comparison suggests a modest potential for discovery of gold deposits at several Colorado Plateau localities.

INTRODUCTION

A significant part of the gold production and reserves from Laramide and younger ore deposits in the Rocky Mountains comes from hypogene deposits associated with alkaline igneous rocks (table 1, fig. 1; Mutschler and others, 1990). In this report we compare the major-element chemistry of these productive alkaline rock suites with chemical data from the igneous rocks exposed in the laccolithic centers of the Colorado Plateau. The comparison suggests a possibility for discovery of alkaline rock-related gold deposits at several Colorado Plateau laccolithic centers, including the Henry and La Sal Mountains and Navajo Mountain, all in Utah.

Alkaline igneous rocks have been defined in many ways, and confusing nomenclature schemes based largely on variations in modal mineralogy abound. In this paper we use whole-rock major-element oxide analyses to define alkaline rocks as those igneous rocks that either (1) have weight percent Na₂O+K₂O > 0.3718 (weight percent SiO₂) – 14.5; or (2) have mol Na₂O + mol K₂O > mol Al₂O₃. Criterion 1 is from Macdonald and Katsura’s (1964) alkalis versus silica plot for separating alkaline from subalkaline basalts (fig. 2). Criteria 2 defines peralkaline rocks in the sense of Shand (1951). Criteria 1 and 2 are independent; that is, peralkaline rocks as defined by criterion 2 need not satisfy criterion 1. Note that silica saturation (the presence or absence of either modal or normative feldspatoids) is not a criterion for alkaline rocks as used here. Alkaline rocks range in composition from relatively primitive kimberlites, lamproites, lamprophyres, and alkali basalts to highly evolved felsic syenites, phonolites, and peralkaline granites, rhyolites, and trachytes.

The worldwide association of a variety of types of gold deposits with alkaline igneous rocks (Mutschler and Mooney, 1993) suggests a genetic relationship. Various possibilities have been suggested to explain the relationship:

1. Parental alkaline magmas may be generated by partial mantle melting at sites where deeply penetrating fault systems extend through the crust (Cameron, 1990).

2. Gold may be transported from the deep mantle by mafic alkaline magmas (Rock and others, 1989).

3. The generally high volatile content of alkaline magmas (Bailey and Hampton, 1990; Webster and others, 1992) could provide ligands for gold acquisition, transport, and deposition (Cameron and Hattori, 1987; Mutschler and Mooney, 1993).

ACKNOWLEDGMENTS

Many colleagues in academia, industry, and government have helped us to compile data on the alkaline igneous rocks of the Cordillera and their associated mineral deposits. For providing us with unpublished material we especially thank James E. Elliott, Fess Foster, Bruce A. Geller, Stephen R. Mattox, Thomas C. Mooney, and Peter D. Rowley. Constructive reviews by Thomas Frost and Steve Ludington helped to clarify both our ideas and our expression.

ALKALINE ROCK-RELATED GOLD DEPOSITS OF THE ROCKY MOUNTAINS

Laramide and younger alkaline rock-related gold deposits in the Rocky Mountains are listed in table 1, and some typical ore-related rock assemblages are plotted on total alkali-silica (TAS) variation diagrams in figure 3. Many of these assemblages include relatively primitive mafic alkaline rocks together with highly evolved or fractionated rocks. This combination suggests that crustal level parking (perhaps at neutral buoyancy levels) and fractionation have been important processes in the evolution of these suites. Coeval calc-alkaline rocks are common at many Rocky Mountain alkaline rock localities (fig. 3E–H) and are predominant at some of them. In many cases the calc-alkaline magmas probably resulted from partial crustal melting by heat and volatiles from mantle-derived alkaline magmas that either ponded in or underplated the crust. In these situations mixing of calc-alkaline and alkaline magmas can produce a variety of hybrid magmas as at the Rosita–Silver Cliff volcanic centers, Colorado (fig. 3H).

Precious metal-bearing deposits associated with Rocky Mountain alkaline igneous centers can be divided into three
### Table 1. Laramide and younger alkaline igneous rock-related gold deposits of the Rocky Mountains.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Igneous rocks</th>
<th>Age in Ma (method)</th>
<th>Ore deposits</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central City–Idaho Springs, Colorado</td>
<td>Alkaline to transitional sodic syenite, quartz syenite, and bostonite stocks; bostonite dikes and breccia-pipes. Coeval calc-alkaline plutons also present.</td>
<td>65–58 K-Ar, Rb-Sr</td>
<td>Zoned district with central pyritic Au veins and breccia-pipe deposits and peripheral polymetallic vein deposits, both of which are probably related to calc-alkaline plutons. Late Au-Ag-Pbtelluride-quartz-fluorite vein and breccia-pipe deposits, U vein deposits, and Mo breccia-pipe deposits related to alkaline plutons. District production 1859–1987: Au, ~171,070 kg; Ag, ~2,278,000 kg; +Cu, +Pb, Zn, U, W. Production from deposits directly related to alkaline rocks 1859–1984: Au, ~3,110 kg; +Ag, Pb, W.</td>
<td>Bastin and Hill (1917) C; Budge and Romberger (1983); Davis and Streufert (1990); Dickin and others (1986), F. E.; Mutschler (unpub. data, 1990) C; Phair and Jenkins (1975) C; Rice and others (1985) C; Rice and others (1982) A; Spurr and Garrey (1908) C; Wallace (1989).</td>
</tr>
<tr>
<td>La Plata Mountains, Colorado</td>
<td>Early calc-alkaline to transitional diorite-monzonite porphyry sills, laccoliths, dikes, and stocks. Younger alkaline stocks include syenite (2), monzonite (1), and diorite (2). Lamprophyre and trachyte dikes, some of which are pre-mineralization, are the youngest igneous rocks.</td>
<td>70–67 K-Ar, FT</td>
<td>Porphyry Cu (Ag, PGE, Au) deposit in syenite stock. Au-Cu skarn and contact breccia deposits. Pyritic Au vein and replacement deposits. Ag-Au bearing polymetallic vein and replacement deposits. Au-Ag telluride vein and replacement deposits. Ruby silver vein deposits. Production 1878–1990: Au, ~6,850 kg; Ag, ~63,360 kg; +Cu, Pb, Zn. Reserves 1990: Au, ~6,875 kg; Ag, ~170,000 kg.</td>
<td>Armstrong (1969) A; Cross and others (1899) C; Cunningham and others (1977) A; Eckel and others (1949); Lux (1977) C; McDowell (1971) A; Mutschler and others (1985); Saunders and May (1986); Werle and others (1984) C.</td>
</tr>
<tr>
<td>Caribou Mountain (Mount Pinos), Idaho</td>
<td>Alkaline shoshonite-diorite subvolcanic plutonic complex.</td>
<td>52–50 K-Ar</td>
<td>Porphyry, skarn, and vein Cu (Au, Ag) deposits. Production 1870s–1959: Au, ~51,860 kg; +Ag, Cu.</td>
<td>Anderson and Kirkham (1931); Hamilton (1961); Huntman (1984, 1988) A.</td>
</tr>
</tbody>
</table>
Table 1. Laramide and younger alkaline igneous rock-related gold deposits of the Rocky Mountains—Continued.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Igneous rocks</th>
<th>Age in Ma (method)</th>
<th>Ore deposits</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goose Lake stock, Cooke City, Montana</td>
<td>Alkaline syenite-monzonite composite stock.</td>
<td>~76 (K-Ar)</td>
<td>Porphyry and pegmatitic Cu (Ag, PGE, Au) sulfide deposits. Major productive precious metal deposits of Cooke City district are related to younger (~40 Ma) felsic plutons and intrusive breccias.</td>
<td>Cordalis (1984); Elliott (1974, 1979); J. E. Elliott (unpub. data, 1983); Holt (1961); Loevinger (1930); F. E. Mutschler (unpub. data, 1983); Mutschler and others (1985); Simons and others (1979); Size (1967).</td>
</tr>
<tr>
<td>Judith Mountains (Warm Spring, Maiden, Gilt Edge), Montana</td>
<td>Older calc-alkaline plutonic suite (69–67 Ma) includes quartz monzonite, monzonite, diorite, and rhyolite. Younger alkaline plutonic suite (65–62 Ma) includes syenite (with cumulate alkali gabbro and Cu-bearing sulfide inclusions), tinguinites (with cumulate olite inclusions), and peralkaline granite.</td>
<td>69–62 (K-Ar)</td>
<td>Au-Ag telluride and native gold vein, limestone replacement, and breccia deposits. Ag-Au bearing polymetallic vein deposits. Disseminated sulfide and skarn Au mineralization at Lister dome. Intense K-metasomatized, disseminated pyrite, and calcite-fluorite-quartz-sulfide-barite-aegirine-scapolite veining in Red Mountain area suggests possible buried carbonatite or alkaline rock-related porphyry metals system. Production 1880–1987: Au, 10,420 kg; Ag, 9,860 kg; +Cu, Pb. Reserves 1988: Au, ~750 kg; Ag, 5,445 kg.</td>
<td>Giles (1983); Goddard (1988); Hall (1976); Kirchner (1982); A; C; Kolart (1991); Lindsey and Fisher (1985); Marvin and others (1980); F. E. Mutschler (unpub. data, 1990); Priesmeyer (1986); Wallace (1953); Weed and Pirson (1898); Zhang and Spry (1991).</td>
</tr>
<tr>
<td>Little Belt Mountains (Nehirat), Montana</td>
<td>Alkaline shoshonite, syenite, monzonite plutons, lamprophyre dikes. Coeval calc-alkaline plutons include high-silica granites and rhyolites.</td>
<td>59–55–46 (K-Ar)</td>
<td>Ag-Au bearing polymetallic vein and replacement deposits. Au skarn deposit. Fe skarn deposits. Au-Ag telluride vein and breccia mineralization. Gem sapphire deposits in hybrid mafic alkaline lamprophyre dikes. Ag (Au) stockwork and disseminated deposit in rhyolite breccia-pipe. Stockwork Mo deposit in high-silica granite-rhyolite intrusive complex. Production 1881–1984: Au, ~2,085 kg; Ag, ~9,420 kg; +Cu, Pb, Zn, gemstones.</td>
<td>Armstrong and others (1982); Baker and others (1991); Brownlow and Komorowski (1988); Clabaugh (1952); Dahl (1991); Embry (1987); C; D; Embry (1987); C; D; Marvin and others (1973); A; Meyer and Mitchell (1988); Olmstead (1991); Pirson (1900); R, Rupp (1980); C; Schutz and others (1988); Walker (1991); Wikind (1970, 1973); C; Woodward (1991);</td>
</tr>
<tr>
<td>Little Rocky Mountains (Zortman-Landusky), Montana</td>
<td>Alkaline and transitional syenite plutons and trachyte dikes. Coeval calc-alkaline monzonite, quartz monzonite, and granite (?) plutons.</td>
<td>67–60 (K-Ar)</td>
<td>Au-Ag electrum and telluride stockwork, breccia, and vein deposits. Production 1884–1989: Au, 35,520 kg; Ag, ~76,000 kg. Reserves 1990: Au, 23,850 kg; Ag, 267,500 kg.</td>
<td>Hastings (1988a); Lindsey and Fisher (1988); Marvin and others (1980); F. E. Mutschler (unpub. data, 1990); Roemmel (1982); C; Russell and Gabelman (1991); Ryzak (1990); Weed and Pirson (1896); C; White and Lawless (1989); Wilson and Kyser (1988, 1989); C.</td>
</tr>
<tr>
<td>Moccasin Mountains (Kendall), Montana</td>
<td>Alkaline to transitional syenite, trachyte plutons and intrusion breccias. Coeval calc-alkaline rocks include rhyolite plutons and intrusion breccias.</td>
<td>66–64, 53 (K-Ar, FT)</td>
<td>Au-Ag telluride and electrum stratouphic (limestone karst breccia) and intrusion breccia deposits. Production 1893–1987: Au, 14,000 kg; Ag, ~6,221 kg. Reserves 1989: Au, 6,800 kg.</td>
<td>Blixt (1933); C; Garverish (1991); Kurisso (1991); Lindsey (1982, 1985); A; C; Lindsey and Fisher (1985); Lindsey and Naeser (1985); A; Marvin and others (1980); F. E. Mutschler (unpub. data, 1990); C.</td>
</tr>
<tr>
<td>Whitehall (Golden Sunlight), Montana</td>
<td>Calc-alkaline (?) latite sills; alkaline trachybasalt hypabyssal plutons. Post-mineralization lamprophyre dikes.</td>
<td>279 (K-Ar)</td>
<td>Epithermal stockwork and disseminated Au-Ag electrum and telluride deposit with Fe, Cu, Pb, Zn, Mo, As sulfides, etc., in hydrothermal breccia-pipe. Zones downward to porphyry-style Cu-Mo (Ag, Au) mineralization. Production 1890–1987: Au, 17,511 kg; Ag, 8,616 kg; +Cu, Pb, Zn. Reserves 1988: Au, 77,760 kg; Ag, ~77,760 kg.</td>
<td>Fess Foster, Golden Sunlight Mines, Inc. (written commun., 1991); A; C; Foster and Chadwick (1990); Porter and Ripley (1985).</td>
</tr>
</tbody>
</table>
types, or deposit models. Attributes of the two end-member models are summarized in table 2. The third, transitional, model can show features of both end-member models.

*Porphyry copper–precious metal deposits.*—These occur in or adjacent to shoshonitic syenite stocks and are characterized by precious metals contained in copper sulfides occurring in stockworks, disseminations, veins, pegmatite dikes and segregations, endoskarns, exoskarns, and local immiscible sulfide concentrations; by relatively high sulfur abundance; and by Cu > Ag > Au or PGE (platinum-group elements). Examples include the Allard stock, La Plata Mountains, Colo. (Werle and others, 1984); the Goose Lake stock, Cooke City, Mont. (Elliott, 1972, 1974; Lovering, 1988); and the Cerrillos district, New Mexico.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Igneous rocks</th>
<th>Age in Ma (method)</th>
<th>Ore deposits</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerrillos, New Mexico</td>
<td>Alkaline monzonite, syenite, diorite plutons; lamprophyre dikes. Coeval (?) latite-trachybasalt volcanics.</td>
<td>Oligocene &gt;27 (K-Ar)</td>
<td>Cu (Ag, Au) porphyry system. Ag-Au bearing polymetallic vein deposits. Turquoise deposits. Production 1902–1956: Au, 43 kg; Ag, 3,890 kg; +Cu, Pb, Zn, gemstones.</td>
<td>Akrighe et al. (1979); Aldrich and others (1986) A; Clarke (1915) C; Disbrow and Stoll (1957); Giles et al. (1991); North and McLemore (1988); Sun and Baldwin (1958) C; Wargo (1964).</td>
</tr>
<tr>
<td>Ortiz (Old Placers), New Mexico</td>
<td>Older (~34 Ma) calc-alkaline suite includes latite-andesite and granodiorite plutons. Younger (30–26 Ma) alkaline suite includes nepheline monzonite plutons, latite plutons and dike swarms, and a diatreme vent breccia.</td>
<td>~34; ~30–26 (K-Ar)</td>
<td>Cu-Ag skarn deposit. Au-Ag (Cu, W) breccia-pipe deposit. Porphry Cu (Au, Ag) deposit. Au-Ag polymetallic vein deposits. Production 1838–1887: Au, ~10,890 kg; +Ag, Cu, Pb, W, Zn. Reserves 1990: Au, 18,560 kg; +Ag, Cu.</td>
<td>Kay (1986) C; Maynard and others (1990) A; Maynard and others (1991) A; Ogilvie (1908) C; Wright (1983).</td>
</tr>
<tr>
<td>San Pedro (New Placers), New Mexico</td>
<td>Alkaline-calc-alkaline syenite, monzonite plutons.</td>
<td>Oligocene</td>
<td>Au-Cu-W skarn deposit. Ag-Pb-Zn limestone replacement deposit. Production 1909–1938: Au, 3,640 kg; Ag, 9,490 kg; +Cu, W, Zn.</td>
<td>Atkinson (1961); Elston (1967); Lindgren and others (1910); North and McLemore (1988).</td>
</tr>
<tr>
<td>White Oaks, New Mexico</td>
<td>Large breccia-pipe complex intruded by alkaline syenogabbro to syenite plutons and lamprophyre plugs and dikes.</td>
<td>34 (K-Ar)</td>
<td>Au-Ag (W) vein, stockwork, and breccia-hosted epithermal deposits. Production 1879–1984: Au, 5,070 kg; +Ag, Cu, W.</td>
<td>Allen and Foord (1991); Griswold (1959); Lindgren and others (1910); North and McLemore (1988); Ronkoski (1991) A.</td>
</tr>
</tbody>
</table>

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1 FT in age method indicates fission track age.
2 A or C following date indicates that reference contains age data (A), or major-element chemical analyses (C).
Figure 1. Rocky Mountain and Colorado Plateau localities discussed in text. Circles are Colorado Plateau laccolithic centers; triangles are Laramide and younger alkaline igneous rock-related gold deposits.
GOLD DEPOSITS IN COLORADO PLATEAU LACCOLITHIC CENTERS

Figure 2. Total alkali-silica plot showing Macdonald and Katsura’s (1964) boundary for separating alkaline and subalkaline rocks, and compositional fields for alkaline rocks related to precious metal deposits and selected other rock types. Arrows show generalized fractionation trends.

Table 2. Attributes of alkaline rock-related precious-metal systems.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Epithermal Au systems (example, Cripple Creek, Colorado)</th>
<th>Porphyry copper–precious metal systems (example, Allard stock, Colorado)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable metals ....</td>
<td>Au&gt;Ag (precious metals usually sole products or major products)</td>
<td>Cu&gt;Ag&gt;PGE or Au (precious metals usually byproducts or coproducts)</td>
</tr>
<tr>
<td>Mineralization</td>
<td>Largely open-space vein filling</td>
<td>Disseminated, pegmatitic, vein, local immiscible sulfides, skarn.</td>
</tr>
<tr>
<td>Au-bearing species ....</td>
<td>Tellurides, native Au</td>
<td>Native Au (largely in sulfides)</td>
</tr>
<tr>
<td>Hydrothermal alteration Facies</td>
<td>Vein envelope and/or pervasive</td>
<td>Pervasive.</td>
</tr>
<tr>
<td>S (as S(^{-2})) abundance ..</td>
<td>Relatively low</td>
<td>High.</td>
</tr>
<tr>
<td>Volatile-element concentrations:</td>
<td>Very high</td>
<td>Moderate.</td>
</tr>
<tr>
<td>Te</td>
<td></td>
<td>Low.</td>
</tr>
<tr>
<td>Tl</td>
<td>High</td>
<td>Low.</td>
</tr>
<tr>
<td>Hg</td>
<td>Generally high</td>
<td>Low.</td>
</tr>
<tr>
<td>As, Sb</td>
<td>Generally high</td>
<td>Variable.</td>
</tr>
<tr>
<td>Ore stage fluids:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>≤210 °C</td>
<td>~300–800 °C.</td>
</tr>
<tr>
<td>Salinity</td>
<td>Low (≥5 wt. % NaCl)</td>
<td>High.</td>
</tr>
<tr>
<td>CO(_2) content</td>
<td>High</td>
<td>High (often saturated).</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>Meteoric dominated</td>
<td>Magmatic dominated.</td>
</tr>
<tr>
<td>Pressure</td>
<td>1–350 bars</td>
<td>~350–1000 bars.</td>
</tr>
<tr>
<td>Source of precious metals</td>
<td>Au from bisulfide and/or telluride complexes; carbonyl complexes(?)</td>
<td>Ag and PGE from chloride complexes; at least some Au late in sequence from bisulfide complexes(?)</td>
</tr>
</tbody>
</table>

(Giles, 1991). In alkaline rock porphyry copper deposits, the precious metals constitute byproducts or coproducts of copper production. Deposits of this type in Mesozoic accreted terranes are being actively mined in British Columbia (McMillan, 1991; Schroeter and others, 1989).

Epithermal gold deposits.—These are generally associated with syenites, trachytes, phonolites, and lamprophyres, and they occur in a variety of settings including volcanic vent complexes, breccia pipes, hot-spring and geyser systems, bonanza veins, and replacements and disseminations in sedimentary and igneous rocks. They are characterized by Au (Ag)-telluride and native gold mineralization, relatively low sulfur abundance, and commonly by Au>Ag. Examples of bonanza epithermal vein deposits include the Cripple Creek district (Loughlin and Koschmann, 1935), the Boulder County telluride camps (Saunders, 1991), and the Bessie G mine in the La Plata Mountains (Saunders and May, 1986), all in Colorado.
Figure 3. Total alkali-silica plots for selected alkaline rock suites related to gold deposits in the Rocky Mountains. Data from references listed in table 1. Boundary between alkaline and calc-alkaline rocks shown by inclined line. Curved arrows show generalized fractionation trends: upper arrow for ore-related alkaline rocks; lower arrow for calc-alkaline rocks. N indicates number of samples.
Noteworthy low-grade bulk-tonnage epithermal deposits include those of the Little Rocky (Russell, 1991), Moccasin (Kurisoo, 1991), and Judith (Giles, 1983) Mountains, Mont.

**Transitional epithermal-mesothermal gold-silver deposits.**—These include disseminated, breccia-pipe, skarn and vein Au-Ag (Cu, Pb, Zn, W) deposits related to syenite-monzonite-diorite plutons. The disseminated deposits range from Au-only porphyry to sedimentary-rock-hosted micron-size Au. Gold mineralization in the porphyry and skarn deposits typically appears to be late in the paragenetic sequence (post-base metal) and to be accompanied by retrograde alteration events. Examples include the Ortiz Mountains (Maynard and others, 1991), Jicarilla Mountains (Allen and Foord, 1991), and perhaps the White Oaks district (Ronkos, 1991), New Mexico; the Red Mountain area, Judith Mountains, Mont. (Hall, 1976); and some of the Tertiary districts in the northern Black Hills, S.Dak. (Paterson and others, 1988).

These three deposit models may represent a vertical (and perhaps short-term temporal) progression. All three types are associated with chemically similar alkaline rocks (see fig. 3) and show similar hydrothermal alteration assemblages (table 2). The ore fluids for both epithermal and porphyry copper–precious metal systems were CO$_2$-rich and relatively oxidized. Fluid inclusions in vein and rock minerals are CO$_2$-rich. Alteration assemblages, both pervasive ones and those found as envelopes around veins, feature carbonate minerals and hematite. Ore-stage gangue minerals commonly include carbonates and sulfates, and negative $\delta^{34}$S values in sulfides are common. The two end-member deposit types differ, however, in Au, Ag, PGE, Cu, and S abundances, in volatile-element concentrations, and in ore-fluid pressure, temperature, and composition (table 2), suggesting that they were deposited from separate fluids. Cameron and Hattori (1987) proposed a scheme for the essentially simultaneous development of two chemically distinct fluids in an oxidized (high $f_{O_2}$), CO$_2$-rich magma chamber, which Mutschler and Mooney (1993) modified to explain the formation of epithermal “gold-only” deposits above and (or) peripheral to alkaline rock-related porphyry copper–precious metal systems. This model is shown diagrammatically in figure 4. A fractionated, oxidized, CO$_2$-saturated alkaline magma chamber exsolves a CO$_2$-rich, highly saline, metal-bearing aqueous fluid, which then unmixes into two immiscible phases: (1) a high-salinity fluid into which Cu, Fe, Ag, and PGE are partitioned as Cl complexes, which can form porphyry copper mineralization with high Ag and (or) PGE values; and (2) a low-salinity H$_2$O–CO$_2$ fluid into which Au (±As, Hg, Sb) is partitioned as S and (or) Te complexes which can form epithermal Au-dominated mineralization.

**Figure 4.** Schematic model for the evolution of two ore fluids from an oxidized CO$_2$-rich alkaline magma chamber. From Mutschler and Mooney (1993).

**PROSPECTING GUIDES**

A variety of gold-bearing deposits are associated with alkaline rocks; consequently various techniques may be useful in prospecting for different types of deposits (Mutschler and Mooney, 1993). Some useful indicators are as follows:

1. The source-host alkaline rocks for both porphyry and epithermal mineralization show evidence of significant crustal-level fractionation; thus chemically diverse suites of alkaline (eralization.

2. Both porphyry and epithermal deposits are accompanied by one or more of the following pervasive hydrothermal alteration assemblages (diagnostic characteristics in parentheses): K-metasomatism (whole-rock K$_2$O>Na$_2$O; hydrothermal K-feldspar and (or) biotite), carbonatite (whole-rock CO$_2$>0.5 weight percent; hydrothermal carbonate minerals; CO$_2$-rich fluid inclusions), redox (whole-rock Fe$_3$O$_4$>1.5 FeO; hydrothermal hematite), $\delta^{34}$S evidence that sulfide S equilibrated with sulfate S, or sulfidization (hydrothermal pyritization and (or) sulfate minerals).

3. Concealed porphyry and skarn deposits, which have relatively high sulfide concentrations, may be recognized by induced polarization surveys.
Table 3. Colorado Plateau laccolithic centers.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Igneous rocks</th>
<th>Age in Ma (method)</th>
<th>Mineralization and alteration</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrizo Mountains, Arizona</td>
<td>Calc-alkaline diorite porphyry laccoliths, sills, and dikes. Younger (Oligocene) mineral plugs and dikes of Navajo volcanic field are also present.</td>
<td>~70 (K-Ar)</td>
<td>Near Pastora Peak, brecciated sandstone cemented by veinlets of quartz overlying fractured diorite porphyry containing sparse pyrite and rare chalcopyrite.</td>
<td>Armstrong (1969) A; Cross (1894) C; Lux (1977) C; O'Sullivan and Beikman (1963); Strobel (1956).</td>
</tr>
<tr>
<td>Ophir–San Miguel–Klondike Ridge, Colorado</td>
<td>West-trending belt of four stocks and many laccoliths, sills and dikes extends from Ophir on the west flank of the San Juan dome to Glade Mountain and Klondike Ridge. Calc-alkaline plutons range from microdiorite to porphyritic adamellite. Oil test wells have intersected buried sills of similar composition in the Paradox Member of the Hermosa Formation. A small andesite vent(?) crops out at Glade Mountain. Post-mineralization lamprophyre dikes occur in the Mount Wilson district.</td>
<td>33–26 (K-Ar)</td>
<td>Two types of productive fissure veins occur in the Iron Springs (Ophir or Ames) and Mount Wilson districts at the east end of the porphyry belt: (1) Gold veins—narrow high-grade pyrite-sericite-quartz-sulfide vein. (2) Silver-base metal veins—galena-sphalerite-pyrite-chalcopyrite-tetrahedrite-quartz-carbonate-barite veins. Vein-envelope and pervasive alteration includes propylitic, quartz-sericite, and pyritic assemblages. Estimated total production since 1882: Au, 3,888 kg; Ag, 28,250 kg; Cu, Pb, Zn, W.</td>
<td>Bromfield (1967) C; Lipman and others (1976) A; McDowell (1971) A; Shawe and others (1968) C; Stomland (1962); Vogel (1960).</td>
</tr>
<tr>
<td>Sleeping Ute Mountain (or &quot;Ute Mountains&quot;), Colorado</td>
<td>Calc-alkaline diorite porphyry forms three stocks, three bymaloliths, and many laccoliths, sills, and dikes. Small dikes and sills of lamprophyre (spessarite) are younger than the diorite porphyry.</td>
<td>~72 (K-Ar, FT)</td>
<td>Minor shear-zone-controlled pyrite-chalcopyrite-quartz-barite veins occur in sandstone. A large part of the Marble Mountain bymalolith has been pyritized, sericitized, and propylitized; small showings of oxide copper minerals are present. Several small travertine-cemented breccia pipes are younger than the lamprophyres and may represent post-Laramide hot-spring activity.</td>
<td>Cross (1894) C; Cunningham and others (1977) A; Ekren and Houser (1965) C.</td>
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<tr>
<td>Abajo Mountains, Utah</td>
<td>Calc-alkaline diorite porphyry forms two stocks surrounded by shatter zones (which include intrusion breccias), many laccoliths, sills, and dikes. Two additional stocks may be present in the subsurface.</td>
<td>32–23 (FT, K-Ar)</td>
<td>Disseminated, stockwork, and vein Au-bearing pyrite-quartz-carbonate (chalcopyrite, sphalerite, galena, ruby, silver?) deposits occur in shear zones in both stocks and at the margins of several laccoliths. Pervasive to shear-zone-controlled propylitic alteration occurs in both stocks and several laccoliths. Alkaline metasomatism altered some East Mountain stock diorite porphyry to alkaline compositions. Minor, undocumented gold production from a few small lode mines and placers.</td>
<td>Armstrong (1969) A; Nelson and others (1992) A; Sullivan and others (1991) A; Witkind (1964) C.</td>
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<tr>
<td>Henry Mountains, Utah</td>
<td>Calc-alkaline to mildly alkaline diorite porphyry occurs in five distinct laccolithic centers at Mounts Ellen, Pennell, Hillers, Holness, and Ellsworth. Each center consists of a central stock, in part surrounded by a zone of shattered intruded sedimentary rocks and diorite porphyry cut by irregular diorite porphyry intrusions; numerous bymaloliths, laccoliths, sills, and dikes. At the youngest center (Mount Pennell, ~25 Ma), the diorite porphyry stock is cut by a complex alkaline syenite porphyry stock, which in turn is intruded by small peralkaline granite porphyry plugs and dikes. The most primitive igneous rock recognized in the Henry Mountains is a basalt porphyry occurring in the shatter zone and as small sills at the Mount Ellen center.</td>
<td>31–23 (Ar/39Ar, FT)</td>
<td>Vein and shear-zone-controlled stockwork and disseminated Cu-Au-Ag deposits have been prospected at all the central stocks and shatter zones. They are most extensively developed at the Mount Pennell and Mount Ellen centers. The hypogene vein assemblage includes pyrite, chalcopyrite, bornite, molybdenite, marmatite, hematite, quartz, and carbonates. Pervasive propylitic alteration occurs in many plutons; pervasive alkaline metasomatism and pyritization have affected central stocks and shatter zones, some of which also show epิดote-amphibole-garnet skarn development. Stilpnomelane is present in mineralized shear zones at the Mount Pennell center. Reported production since 1889 from Mount Ellen (Bromide Basin): Au, 21 kg; Ag, 93 kg; Cu, 8.2 Mg. Mount Pennell lode production since 1925: Au&lt;1 kg. Small amounts of placer gold are reported to have been recovered from streams draining Mounts Ellen and Pennell.</td>
<td>Butler and others (1920); Cross (1894) C; Doelling (1980); Dubiel and others (1988a, b, 1990) A; Engel (1959) C; Hunt and others (1953) C; Hunt (1988) C; Kiliner (1979) C; Nelson (1991) C; Nelson and Davidson (1993) C; Nelson and others (1992) A; Sullivan and others (1991) A</td>
</tr>
</tbody>
</table>
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GOLD DEPOSITS IN COLORADO PLATEAU LACCOLITHIC CENTERS

Mountains, Ariz. as Colorado Plateau features. In a similar fashion, we have excluded the middle Tertiary West Elk Mountains, Colo., laccoliths from the Colorado Plateau.

Data on the lithology, form, age, and associated mineralization of the igneous rocks in the Colorado Plateau laccolithic centers (fig. 1) are summarized in table 3. Total alkali-silica (TAS) plots for those laccolithic centers for which whole-rock chemical analyses are available are shown in figure 5. Most of the igneous rocks fall into two groups:

1. Dominantly calc-alkaline intermediate (55–65 weight percent SiO₂) rocks, here collectively termed diorite porphyry. Different investigators have applied various names to these rocks, including diorite-monzonite porphyry, diorite porphyry, granodiorite, granodiorite porphyry, microgabbro, microgranogabbro, monzonite porphyry, plagioclase-hornblende porphyry, porphyritic adamellite, quartz diorite porphyry, and quartz monzonite porphyry. Diorite porphyry forms concordant plutons, including laccoliths and sills, and discordant stocks, dikes, and brysmaliths. It constitutes more than 90 percent of the igneous rocks exposed in the major laccolithic centers of the Colorado Plateau (Hunt, 1956; Hunt and others, 1953) and adjacent areas. On TAS plots most of the diorite porphries fall within the compositional fields of the mid-Tertiary

4. Low-sulfide “invisible,” or micron- (micrometer) size Au deposits may be recognized by geochemical anomalies in Au (>10 ppb) and some of the following: Ag, As, Bi, Ce, F, Hg, Sb, Se, Te, Ti, U, V, W, and high Ba and Sr in Ba: Sr: Rb ratios. Gold, commonly at levels in the parts-per-billion range, is the only universal geochemical guide to ore; concentrations and dispersion halos of other “pathfinder” elements can vary widely from deposit to deposit, even within a single district (Mutschler and others, 1985).

ALKALINE ROCKS AND MINERALIZATION IN THE COLORADO PLATEAU LACCOLITHIC CENTERS

Depending on how the borders of the Colorado Plateau are defined, laccolithic centers on the plateau can be enumerated differently. We have somewhat arbitrarily considered that the Laramide-age La Plata, Ouray, and Rico laccolithic centers in Colorado are Rocky Mountain features, whereas we have included the Laramide age Sleeping Ute Mountain (or “Ute Mountains”), Colo., and Carrizo

Table 3. Colorado Plateau laccolithic centers—Continued.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Igneous rocks</th>
<th>Age in Ma (method)</th>
<th>Mineralization and alteration</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Sal Mountains, Utah</td>
<td>Calc-alkaline to mildly alkaline diorite porphyry occurs in three laccolithic centers at North, Middle, and South Mountains. Each center has a central stock, several peripheral laccoliths and/or brysmaliths, and dikes and sills of diorite porphyry. At the North Mountain center the diorite porphyry is cut by a small stock and dikes of alkaline syenite porphyries. Emplacement of the syenites was accompanied by hydrothermal alteration and mineralization. A single syenite porphyry laccolith/sill is present at the Middle Mountain center. A group of explosion breccia pipes associated with small peralkaline granite and rhyolite porphyry plutons formed during or shortly after the emplacement of the alkaline syenite porphyries. Coeval peralkaline rhyolite and rhyolitic trachyte porphyry dikes mark the final magmatic event at North Mountain.</td>
<td>28–25 (⁴⁰Ar/³⁹Ar, FT)</td>
<td>Fissure vein and fracture-zone-controlled stockwork and disseminated Cu-Au-Ag deposits have been prospected at all three centers. Alteration and mineralization are most extensively developed at North Mountain, where they accompanied emplacement of the syenite porphyries. Here pervasive and vein envelope alkali metasomatic, pyritization, carbonatic, and redox assemblages are widespread. Hypogene vein minerals include pyrite, chalcopyrite, bornite, hematite, quartz, carbonates, and fluorite. A second stage of carbonate, hematite, and silica alteration and minor sulfide mineralization accompanied formation of the explosion breccia pipes at North Mountain. Small ore shipments were made from several North Mountain mines, but production figures are not available. Traces of placer gold occur in pre-Wisconsin gravels derived from North and Middle Mountains.</td>
<td>Armstrong (1969) A; Butler and others (1920); Cross (1894) C; Hunt (1958) C; Irwin (1973) C; Nelson (1991) C; Nelson and others (1992) A; Stern and others (1965) A; Sullivan and others (1991) A</td>
</tr>
<tr>
<td>Navajo Mountain, Utah</td>
<td>Small alkaline quartz-bearing syenite porphyry intrusion exposed on southwest side of ~10-km-diameter dome probably uplifted by emplacement of buried pluton.</td>
<td>No data</td>
<td>Primary hematite in syenite indicates crystallization at high-Po conditions. Most of the sedimentary rocks exposed on the top of the dome are highly silicified.</td>
<td>Condie (1964)</td>
</tr>
</tbody>
</table>

¹ FT = fission-track.
² A or C following date indicates that reference contains age date (A), or major-element chemical analyses (C).
Figure 5 (above and facing page). Total alkali-silica plots for Colorado Plateau laccolithic centers. Data from references listed in table 3. Boundary between alkaline and calc-alkaline rocks shown by inclined line. Curved arrows show generalized fractionation trends: upper arrow for ore-related alkaline rocks; lower arrow for calc-alkaline rocks. \( N \), number of samples.
calc-alkaline volcanics and plutons of the San Juan volcanic field, Colorado, as shown in figure 6. Many of the diorite porphyry analyses that plot significantly above the alkaline-subalkaline rock divider in figure 5A, E, G, and H reflect post-crystallization alkali metasomatism, including albitization (Nelson and Davidson, 1993) and potassic alteration (represented by secondary potassium feldspar and (or) biotite).

2. Alkaline intermediate (55–65 weight percent SiO₂) rocks, here collectively termed syenite porphyry. These rocks occur at the Mount Pennell center in the Henry Mountains and at the North and Middle Mountain centers...
in the La Sal Mountains, Utah, forming stocks, sills, irregular plutons, and dikes, all of which are younger than the diorite porphyry plutons. In addition to these well known localities, Condie (1964) has described a small quartz-bearing, highly oxidized, syenite porphyry pluton on the southwest flank of the Navajo Mountain dome, Utah. Both nepheline- and quartz-normative syenite porphyries are present in the La Sal and Henry Mountains. Although most of the La Sal syenite porphyries are peralkaline, none of the analyzed Henry Mountain syenite porphyries are. The syenite porphyries of the Henry and La Sal Mountains are chemically distinct from, and have no counterpart in, the voluminous coeval mid-Tertiary rocks of the San Juan volcanic field of southwestern Colorado, as shown by comparing the TAS plots of figure 5D, H, and I with figure 6. In fact, in both the San Juan, Colo. (Mutschler and others, 1987), and Marysvale, Utah (Mattox, 1992; Rowley and others, this volume), volcanic fields, alkaline magmatism is essentially restricted to bimodal (alkali basalt/trachybasalt-rhyolite) suites, which began to erupt during the onset of extensional faulting at =23 Ma.

Nelson and Davidson (1993) have presented isotopic evidence that both the diorite porphyry and syenite porphyry magmas of the Henry Mountains were derived from the same mantle source, but that they probably represent different degrees, or depths, of partial melting. According to Nelson and Davidson the parental magmas for the two suites reacted with, and assimilated, crustal rocks at different parking levels.

Pervasive hydrothermal alteration and local base- and precious-metal mineralization followed emplacement of the syenite porphyry stocks at both the North Mountain center in the La Sals and the Mount Pennell center in the Henry Mountains (Hunt, 1958; Hunt, 1988; Irwin, 1973; Nelson and others, 1992). Propylitic (chlorite-calcite-epidote-magnetite-hematite) alteration generally extends farthest from the stocks. Other, generally more proximal, pervasive alteration assemblages include hornfels skarn (aegirine-augite, riebeckite, glaucophane, hedenbergite, actinolite, biotite, magnetite, hematite, garnet), alkali metasomatism (albitization and subordinate potassium feldspathization), carbonatic alteration (calcite, siderite?), redox alteration (hematitization), and sulfidization (pyrite-base-metal sulfides). Narrow breccia zones and small fissure veins occur locally, commonly following sheeted zones. Hypogene vein minerals include quartz, carbonates, fluorite, Au-bearing pyrite, chalcopyrite, bornite, galena, sphalerite, molybdenite, magnetite, and hematite. Similar but less intense alteration and mineralization occurred in and adjacent to some diorite porphyry plutons at most of the other Colorado Plateau laccolithic centers. (See table 3.)

At the North Mountain center in the La Sals the alteration and mineralization caused by the syenite porphyry were accompanied and also followed by formation of the breccia pipes (volcanic vents?) and coeval small peralkaline rhyolite porphyry plutons and dikes (Ross, 1992). Several of these pipes exceed 500 m in maximum horizontal dimension. A second alteration and mineralization event is represented by disseminated hematite, minor vein chalcopyrite and pyrite, and vug and cone sheet-fracture filling by calcite and quartz in the pipes. At North Mountain, the final intrusive phases are late-stage to postmineralization peralkaline rhyolite porphyry and nesoschist porphyry dikes that crosscut most intrusive phases, breccia pipes, and pervasively altered areas (Ross, this volume). Peralkaline granite also occurs as the youngest intrusive phase in the Mount Pennell center of the Henry Mountains, where Hunt (1988) suggests it preceded or accompanied mineralization.

**EXPLORATION POTENTIAL FOR GOLD IN THE COLORADO PLATEAU LACCOLITHIC CENTERS**

Three features that are characteristic of productive alkaline rock-related gold deposits in the Rocky Mountains (tables 1, 2) are also present in the Colorado Plateau laccolithic centers:

1. The centers include highly fractionated alkaline plutons such as the syenites of Mount Pennell in the Henry Mountains, North Mountain in the La Sals, and Navajo Mountain. Evolved peralkaline granites and rhyolites are also present at Mount Pennell and North Mountain.

2. Pervasive hydrothermal alteration, including alkali metasomatism and propylitic, carbonatic, redox, pyritic, and silicic alteration, has been reported at most of the laccolithic centers.

3. Subeconomic occurrences of hypogene gold have been recognized in the Abajo and San Miguel centers.

In the last decade, several major mining companies have evaluated the precious metal potential of the Colorado Plateau laccolithic centers with geochemical surveys, and, in the La Sal Mountains, with drilling programs. Although some geochemical anomalies and limited mineralized drill intercepts have been found, no economic ore deposits were discovered. However, relatively large areas of geologically suitable terrain remain untested, especially for low-sulfide, low-grade gold deposits. Inasmuch as such "invisible" deposits are still being discovered in and adjacent to well-studied mining camps (see Tooker, 1990, for example), we conclude that a modest potential exists for finding economic alkaline rock-related gold deposits in the laccolithic centers of the Colorado Plateau.
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