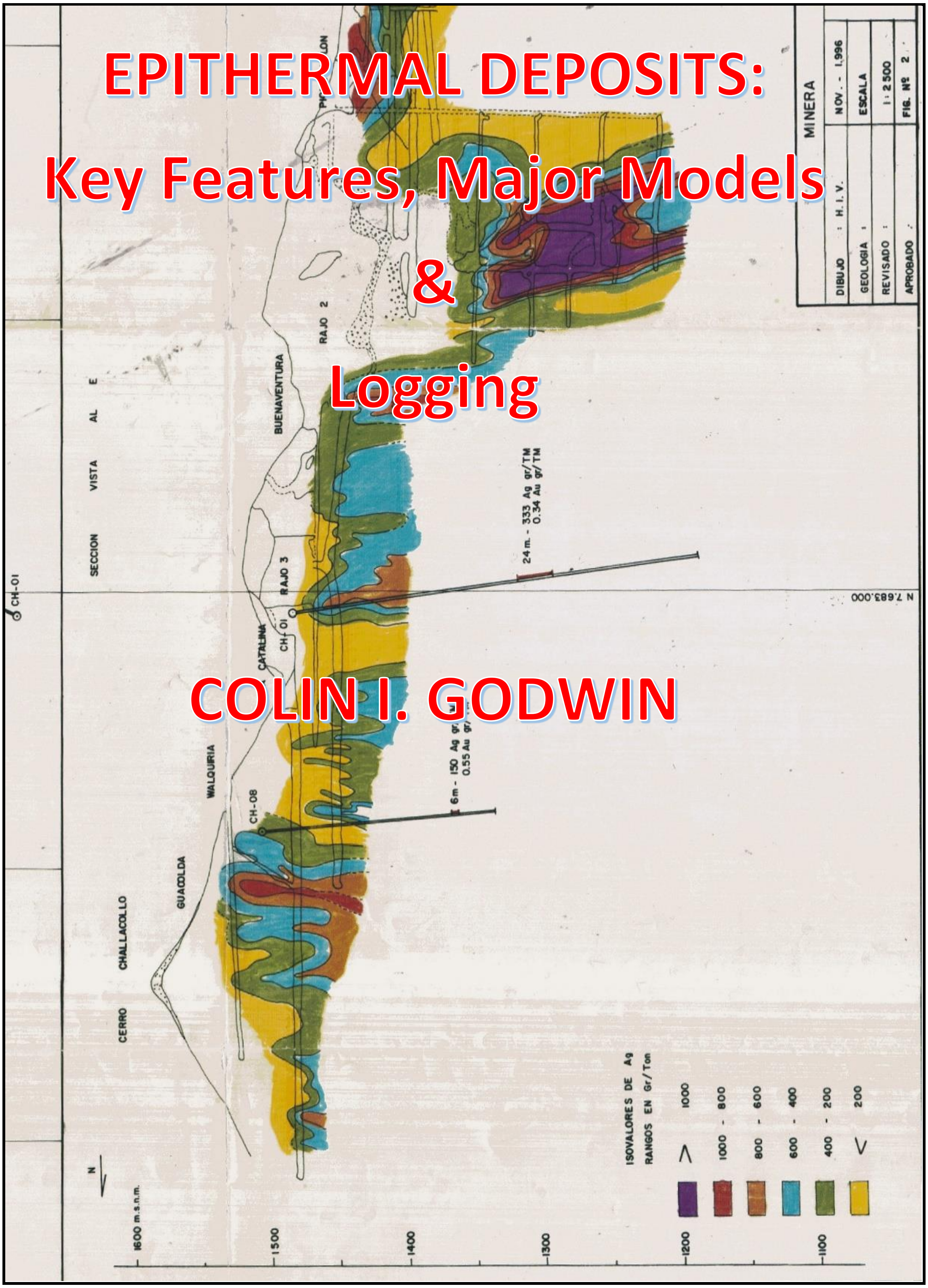
EPITHERMAL DEPOSITS:

Key Features, Major Models & Logging



COLIN I. GODWIN

This guide demonstrates *how to identify and describe key features of epithermal deposits. Emphasis is on recognizing and understanding the origin and importance of exploration-relevant field observations without the aid of sophisticated instrumentation.*

Topics emphasizing field observations related to porphyry deposits include *a) identification of habits (textures or modes of occurrence) that aid in the concise description and recording of geology, alteration and ore mineralization, b) theoretical features of alteration and mineral deposition, c) essential aspects of deposit emplacement, and d) major deposit models of porphyry deposits that include exploration vectors to ore location.*

This guide will help:

- ***geologists and experienced prospectors*** *wanting to upgrade or learn new exploration field skills, especially those involved in evaluating epithermal prospects,*
- ***exploration managers*** *looking to train groups of field geologists to a higher level of expertise in exploration methodology and pattern recognition of vectors to ore zones,*
- ***geologists and managers*** *needing advanced and consistent coordination and efficient field exploration, and*
- ***executives or investors*** *involved in exploration ventures who need an overview of how best to understand, conduct and enhance field exploration.*

Cover is a cross-section field map showing silver values in the epithermal Challacollo silver vein, northern Chile.

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EPITHERMAL DEPOSITS:
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CONTENTS

INTRODUCTION

In this guide you will learn

- ➔ **general sources for detailed descriptions of epithermal deposits,**
- ➔ **the framework for this guide on epithermal deposits, and**
- ➔ **some basic definitions related to epithermal deposits.**

Part of this guide looks at key features of the geology and alteration of epithermal deposits that can be identified in the field without the use of expensive, sophisticated instruments. The objective of this guide is to provide a framework for understanding generalized features common to epithermal deposits, and present mechanisms and models that help to explain how ore location and deposit-related features are formed.

Codes and formats that facilitate field mapping and drill hole logging are in Appendices A and B. A problem set is presented in Appendix C.

References for extensive, detailed, and voluminous compilations of the geology and alteration of epithermal deposits—required references for the serious epithermal explorationist—include:

- Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M. and Hickey, K.A. (2005): Carlin-type gold deposits in Nevada: critical geologic characteristics and viable models; *in* Hedenquist, J.W., J.F.H. Thompson, R.J. Goldfarb and J.P. Richards (eds.), 100th Anniversary Volume, Economic Geology, p. 451–484.
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- Thompson, A.J.B. and Thompson, J.F.H. (eds., 2015): Atlas of alteration: a field and petrographic guide to hydrothermal alteration minerals; *in* Dunne, K.P.E. (Mineral Deposit Division Series Editor), Geological Association of Canada, 119 p.
- White, D.E. (1981): Active geothermal systems and hydrothermal ore deposits; *in* Skinner, B.J., (ed.), 75th Anniversary Volume, Economic Geology, p. 392–423.

Definition of an epithermal deposit (*epi* = surficial and *thermal* = hot; therefore, *epithermal* = a hot, hydrothermal and near-surface origin) was made by Lindgren (1933; see insert *Did you know? Lindgren and epithermal deposits*). Epithermal deposits form from near-surface (1 to 3 kilometres in depth—much shallower than, and sometimes above, porphyry deposits) hydrothermal fluids, or related vapours, with precipitation temperatures from about 150°centigrade to 350°centigrade, which would most commonly appear at the surface as hot springs in areas of active volcanism. Due to their shallow depth of formation, they are susceptible to erosion, which has the consequence that epithermal deposits are commonly, but not exclusively, Cenozoic. Epithermal deposits contain economic concentrations of gold more than silver, and lesser amounts of base metals, which may include copper, and/or lead and zinc. Epithermal gold—commonly found as native gold or alloyed with silver (electrum)—contributes significantly to the world's gold supply. As a result, epithermal deposits are important exploration targets.

Did you know? Lindgren and epithermal deposits.

Dr. Waldemar Lindgren (cf. 1933), a founder of modern economic geology, proposed the term 'epithermal' to describe orebodies deposited at shallow depths from ascending mineralizing hydrothermal solutions. He noted similarities to hot spring deposits, dimensions greater longitudinally than vertically, common relation to Cenozoic volcanism and crustiform and comb textures. Epithermal deposits were his forte. For example, he described 'angel wing' texture but called it 'lamellar texture'.

Formation of an epithermal deposit requires a) a fracture system to facilitate hydrothermal flow, b) a heat source and sustained flux of metal-rich hydrothermal fluids, and c) an efficient precipitation mechanism. The majority of epithermal silver deposits present wallrock alteration patterns like those in modern geothermal systems with sequences related to those in porphyry deposits. In general, hydrothermal fluids travel up through upwardly flaring fractures that become mineralized as fluids rise and minerals precipitate.

Two major types of epithermal deposits are high-sulfidation and low-sulfidation types; intermediate-sulfidation deposits are a cousin of low-sulfidation deposits and are characteristically enriched in silver, lead, and zinc. High-sulfidation deposits are often formed from magmatic fluids that are oxidized and acidic (i.e., low pH). Low-sulfidation deposits are dominated by geothermal fluids that are a mixture of percolated groundwater and magmatic fluids, which tend to be reduced and neutral in pH. Some authors subdivide epithermal deposits based on metal types, such as gold-rich, silver-rich and base-metal–rich, but these subdivisions are not pursued here.

Additional types of epithermal deposits include a) disseminated deposits in porous-permeable sedimentary or volcanic rocks (such as carbonaceous tuffs and carbonaceous-silty sandstone), b) thrust-detachment–related veining, and c) Carlin-type deposits. Volcanogenic massive sulfide deposits (**VMS**) and sedimentary exhalative deposits (**SEDEX**) are epithermal in the sense that they form surficially, albeit on the ocean floor; however, these latter two types are not discussed here because most geologists restrict the use of the term epithermal deposits to deposits formed in a continental setting.

Epithermal deposits that are mined are typically small, high grade and near the surface. Mineralization in orebodies can be disseminated, contained in an upwardly branching network or stockwork of veins, or confined to larger veins that sometimes exhibit ore shoots and areas with local bonanza grades of silver and gold. High-grade veins, with gold values from about 10 to more than 150 grams per tonne, are commonly mined underground. Near the surface, zones might have low grades, on the order of 1 to 3 grams per tonne, but are large, as much as 200 million tonnes, and can be mined by bulk mining methods such as open pits. A rule of thumb is that a prospect of interest to a major company should have in sight at least 30 million grams of gold (about 1 million troy ounces). Another rule of thumb is that underground operations need probable gold grades, at least locally, approaching no less than 5 grams per tonne gold (and preferably more) over mining widths of at least 2 metres. Key ore grades can be related to chimneys or stopes where sulfide content, metal grades, orebody width and vertical extent of mineralization are greatest. Intervening areas can be of lower grade, where orebodies tend to be smaller. In addition, epithermal vein systems are commonly erratic, and correspondingly require detailed exploration to define tonnage and grade. This can be related to variable precious-metal sources, complicated fracture systems and diverse silicification and alteration systems. Eimon (1981) noted that this can be a geostatistician's dream, but a nightmare for mine management.

Recovery of precious metals from epithermal deposits is largely dependent on mineralogy. Native gold and gold-bearing sulfides can be recovered by gravity methods (e.g., jigs and shaking tables) and froth flotation. Supergene alteration of sulfides to oxides facilitates heap leaching. Heap leaching using cyanide is standard for open-pit oxide mines but cyanide can be environmentally challenging; an alternative method, sulfurous thio-complex leaching, is being developed. Micron gold, silica encapsulation of very fine gold and hypogene mineralization (including arsenopyrite-rich gold deposits) can be difficult to process and require special processes such as pressure leaching and/or roasting. Arsenic-rich ores can be environmentally problematic.

A summary of the general characteristics of precious-metal epithermal mineral deposits follows in TABLE 1.

TABLE 1. Main characteristics of vein or bulk-mineable precious-metal epithermal ore deposits.
Descriptions related to Carlin-type deposits are in italics.

Feature	**Description**
Host rocks	**Cenozoic volcanic rock**, often andesite and rhyolite, are common. Volcanic rocks are commonly calcalkaline, but alkaline associations are also important. Intrusive and metamorphic rocks are less common. **Aquitards** that guide hydrothermal fluids, and porous-permeable units able to focus precipitation and host precious metals, can be significant. **Breccias** are particularly significant because they are porous and permeable, and form—and host ore—from mineralizing hydrothermal fluids; higher grade ores are commonly hosted within epithermal breccias. ***Carlin-type deposits****, hosted in carbonaceous carbonate rocks (commonly collapsed and decalcified), are arguably a type of epithermal deposit. They are treated as such here*.
Mode of occurrence	**Modes of occurrence include** veins, lamellar quartz veins, stockwork, pipes and breccias, disseminations, and replacements. Veins are commonly erratically discontinuous and tend to branch upward with increasing complexity. ***Carlin-type mineralization*** *includes veins, replacements, and collapse-dissolution breccias.*
Dimensions	**Vertical extents** are commonly a maximum of 1,000 metres but are typically 200 to 300 metres. Horizontal extents have a maximum of about 3,000 metres and are typically 150 to 1,000 metres in operating mines. **Underground mining widths** are typically between 1 and 3 metres, whereas open pits may mine zones of stockwork or sheeted veins from 10 to more than 100 metres wide. Ore shoots are often horizontally related to a water table, but they can also be cigar or lens shaped of variable orientation. As a rule of thumb, ore shoots within an individual vein commonly involve only one-fifth to one-tenth of the volume of the hosting vein, and the location of the ore shoot is commonly controlled by the intersection of the vein with a crossing structure that is commonly another vein. **Size and shape of ore shoots** can be associated with dilation related to movement on non-planar faults.
Structural setting	**Structures and breccias** may be related to maars and calderas. Regional dilation areas from pull-apart structures are important. Movement on bent faults commonly forms openings filled by veins. Quartz 'flat makes' are horizontal veins common to some gold deposits. **Thrust detachment zones** and related structures—especially listric normal faults—can be significant, and interpretation demands a regional mapping framework. ***Carlin-type deposits*** *occur characteristically at the intersection of deep linear faulting associated with intrusive gold sources with a carbonaceous-sedimentary hinge-line chemical trap.*
Gangue minerals	**Common gangue minerals** include adularia, amethyst quartz, 'angel wing' calcite, 'angel wing' quartz, barite, calcite, carbonate, chalcedony and agate quartz, fluorite, limonite, manganese wad, marcasite, pyrite, pyrrhotite, quartz, quartz opal ,

	rhodochrosite, siderite and zeolite. ***Carlin-type gangue*** *includes arsenopyrite, calcite (organic-rich and collapse-decalcified), limonite, marcasite, orpiment, pyrite (arsenian), quartz, jasperoid quartz, realgar, scorodite, and variscite.*
Ore minerals and secondary minerals	**Common ore minerals** include acanthite, bindheimite, cerargyrite, chalcopyrite, cinnabar, enargite, galena, gold-silver tellurides (and selenides), native electrum, native silver, native gold, pyrargyrite (proustite), realgar, sphalerite, stibnite, and tennantite-tetrahedrite (called freibergite if silver rich).
Type models	**Type models** detailed in this guide are Buchanan, high-sulfidation, low-sulfidation and thrust-detachment and related structures. ***Carlin-type models*** *are elaborated upon in this guide.*
Index fossils for epithermal deposits	**Seven 'index fossils'** described in this guide are adularia, amethyst, angel-wing calcite or angel-wing quartz, black matrix breccia, ginguro habit, gusano habit in quartz-pyrophyllite lithocap, and spongy residual-quartz lithocap. ***Key Carlin-type mineral associations*** *are arsenian pyrite, arsenic-antimony-mercury minerals, phosphate minerals (e.g., variscite) and jasperoid*.
Classic high-sulfidation deposits	Goldfield, southwestern Nevada, United States (GF in Figure 34). El Indio, Chile Yanacocha, Peru (Longo et al., 2010; Teal and Benevides, 2010)
Classic low-sulfidation deposits	Mount Skukum, southwestern Yukon, Canada Comstock, northwestern Nevada, United States Round Mountain, central Nevada, United States (RM in Figure 34) Creede, Colorado, United States McLaughlin, northwestern California, United States Hishikari, Japan
Associated deposit types	Intermediate-sulfidation epithermal deposits Porphyry deposits at depth Placer deposits ***Carlin-type:*** *low-grade gold in porous/permeable, commonly carbonaceous, or pyritic, sedimentary, and sedimentary-volcanic rocks; possibly porphyry gold deposits at depth.*
Classic thrust–detachment deposits	La Jojoba, northern Sonora, Mexico Bullfrog, southwestern Nevada, United States (BF in Figure 34)
Classic Carlin-type deposits	*Carlin, northern Nevada, United States (CR in Figure 34).* *Gold-Quarry, northern Nevada, United States (GQ in Figure 34).* *Cortez, central Nevada (CZ in Figure 34).*

Description of epithermal deposits in this guide emphasizes common-sense principles that are applicable to field exploration without recourse to fluid inclusion microscopes, isotopic analyses, thin and polished section microscopy, X-ray fluorescence (XRF), X-ray diffraction (XRD), short-wave-infrared spectroscopy (SWIR) or other technological tools. The description of epithermal deposits in this guide is presented in the following sections:

1. **Key features of epithermal deposits**: a) commonly associated host rocks, b) importance of structure, c) practical chemical and physical constraints and d) seven must-look-for 'index fossils'.
2. **Classic alteration zones in epithermal deposits**: a) generalized, classical lithocap alteration, and b) generalized, classical hypogene zones.
3. **Idealized models of alteration in epithermal deposits**: a) classic Buchanan model, b) classic high-sulfidation model, and c) classic low-sulfidation model.
4. **Overpressure thrust-detachment model:** a) the significance of the soda can model of thrusting, b) relationships of epithermal deposits to thrust-detachment faults, and c) boiling in listric normal fault-splays from thrust-detachment faults.
5. **Carlin-type gold deposits**: a) the general characteristics of Carlin deposits, b) a likely magmatic source for gold-bearing hydrothermal solutions, c) a carbonaceous trap that precipitates gold from hydrothermal solutions, d) the formation of Carlin-type deposits at the intersection of source and trap, and e) a generalized model for Carlin-type deposits.

Be sure you understand from this section that:

- ➔ **there is abundant, detailed literature on epithermal deposits,**
- ➔ **this guide is field oriented, and**
- ➔ **there are different types of epithermal deposits.**

KEY FEATURES OF EPITHERMAL DEPOSITS

In this section you will learn:

- ➔ **commonly associated host rocks of epithermal deposits,**
- ➔ **importance of structure in epithermal deposits,**
- ➔ **practical chemical and physical constraints of epithermal deposits, and**
- ➔ **seven must-look-for index fossils for epithermal deposits.**

Four framework features for understanding epithermal vein systems are detailed below. They are:

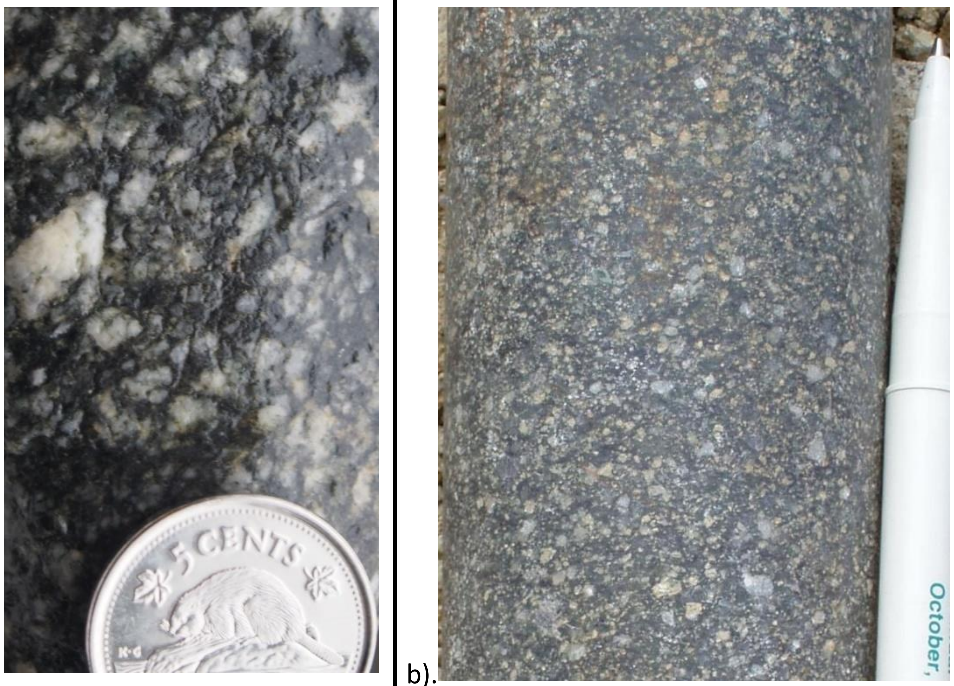
- commonly associated host rocks that include volcanic, porphyry, hydrothermal breccias and carbonaceous carbonate,
- dilatant zones due to faults at regional and local scales,
- practical chemical and physical constraints to mineral deposition, and
- seven must-look-for 'index fossils': adularia in veins or vugs, amethyst in veins or vugs, angel wing texture, black matrix hydrothermal breccia, ginguro colloform texture, gusano texture in quartz-pyrophyllite, and residual-quartz lithocap.

Associated Host Rocks: Volcanic, Porphyry, Hydrothermal Breccia and Carbonaceous Carbonate

Volcanic rocks in epithermal deposits are either calcalkaline or alkaline. They are generally Cenozoic because young volcanic rocks are most likely to have survived erosion (i.e., older rocks are more likely to have eroded away). Andesites are common hosts to vein deposits, in part because of their iron content and fewer fractures that focus fluid flow. Rhyolite flows and domes and porphyritic rocks are important as sources for hydrothermal fluids and heat. Breccias are always significant because they can be formed from mineralizing hydrothermal fluids and can provide open spaces for metal precipitation. Permeable and porous rocks are important hosts for gold mineralization. Host rocks containing reductants, such as carbon or iron, can be particularly important because they allow the reduction of gold from hydrothermal solutions by coupled oxidation-reduction, or by desulfurization (pyritization) of gold hydrothermally transported as sulfurous thio-complexes.

sulfurous thio-complexes.

Porphyritic rocks, illustrated in Figure 1, are significant in epithermal deposits (see insert *Definitions of porphyritic habit and porphyritic rock names*). Distinguishing porphyry from some crystal tuffs and ignimbrites can be a challenge (compare Figure 1a to Figure 1b); thin section examination and assessment of outcrop-scale bedding can aid with identification. Porphyritic rocks generally occur as stocks or dikes and are often genetically related to breccias. The main steps to classifying porphyritic rock are a) defining porphyritic dikes as pre-mineralization, syn-mineralization or post-mineralization, and b) identifying the minerals in the porphyritic rock that are indicative of a hydrous and/or late differentiation stage origin. Mapping is needed to determine the timing of dikes with respect to mineralization. Hydrous porphyries are likely to be more ore productive than dry porphyries. Hydrous nature can be gauged by a) an abundance of hydrous mineral phases (e.g., biotite is more hydrous than hornblende) and b) the degree to which mineral components are late differentiates as indicated by abundant K-feldspar and albite. Hydrous or productive porphyries have positive correlation with hydrothermal alteration (including ore mineralization) and breccia formation.



a) b).

Figure 1. Example of a) porphyritic habit compared to b) crystal tuff from a volcanic-hosted epithermal deposit.
a) *Distinct feldspar phenocrysts are present in this feldspar porphyry from Gambier Group, British Columbia, Canada.* ***b)*** *Feldspar-crystal tuff in core from the Round Mountain low-sulfidation epithermal deposit in central Nevada, United States (RM in Figure 34). The distinction between porphyry and tuff can be difficult; thin section examination and assessment of outcrop-scale bedding can aid with identification.*

Definitions of porphyritic habit and porphyritic rock names.

Porphyritic habit (Figure 1a) refers to any igneous rock marked by conspicuously large crystals (called phenocrysts) dispersed in a relatively fine-grained matrix or groundmass. Such a rock is called porphyry or porphyritic. **Porphyritic rock names** are commonly based on prominent phenocrysts. For example, quartz porphyry, feldspar porphyry, and quartz-feldspar porphyry are common names for porphyritic rocks with prominent quartz, feldspar, and quartz and feldspar phenocrysts, respectively.

Timing of intrusion for these rocks as stocks and dikes is important and leads to their classification as pre-, syn- or post-mineralization, which can be determined by careful field mapping. Some porphyritic dikes and stocks explode into breccia. They can also exude hydrothermal fluids, leading directly to ore mineralization and alteration.

Hydrothermal breccia dikes and pipes or diatremes (see insert *Definitions of breccia, breccia pipes, hydrothermal breccia, collapse breccia, fault breccia, pseudobreccia or crackle breccia, and sedimentary breccias and conglomerate*) are as important in epithermal deposits as they are in porphyry deposits. They can occur in numerous situations, but they are often related to maars, calderas, domes, stocks, and dikes. They form from explosion of magmatic gases in associated magma, and sometimes from the explosion of groundwater heated by intrusive rocks.

Crack-seal mechanism (Figure 2) in the formation of epithermal breccias is common. Crack-seal involves plugging of a hydrothermal system by quartz, which causes heat and pressure to build up. When the vapour pressure exceeds the lithostatic pressure and tensile strength of the surroundings, or when the sealed pressure is tapped by a fracture such that the vapour pressure changes from lithostatic to hydrostatic, the rocks rupture like an exploding pressure cooker and breccia bodies are formed. These crack-seal episodic events follow the sequence:

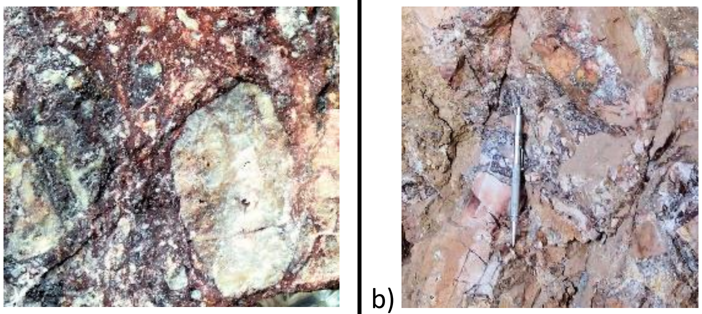
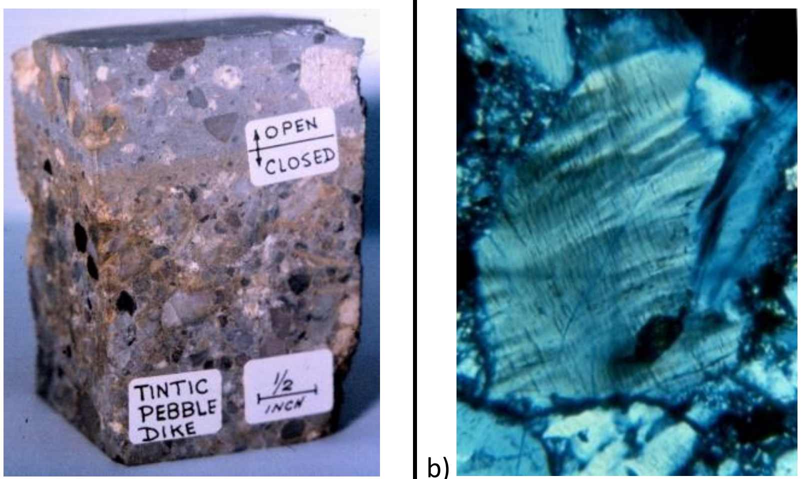

a) b)

Figure 2. Multi-event breccia from the Challacollo silver mine in northern Chile.
a) *The white, subrounded quartz fragment is about 3 cm long, is brecciated and has a vuggy core; it represents pre-breccia silicification that likely was system sealing. Pressure builds up caused fracturing of the silicified seal and brecciation.* ***b)*** *A black matrix hydrothermal breccia with large fragments cut by a later stage of mineralization that might also contribute to grade. Multiple events of silicification and brecciation are attractive because every event can contribute economic mineralization of silver and/or gold.*

1. Quartz seals a permeable fracture system.
2. Continued heating from an underlying intrusion builds pressure within the sealed system.
3. The system brecciates like an exploding pressure cooker and ore mineral precipitation occurs because of adiabatic cooling and vapour release.
4. The system reseals with quartz.
5. The system explodes again, resulting in re-brecciation, commonly with additional ore mineral precipitation.
6. The process repeats if conditions remain the same or similar.

Brecciation and fracturing are integral to maar and caldera formation; consequently, many epithermal deposits are closely related to maars and calderas. Maars are low-relief volcanic craters caused by phreatomagmatic eruptions driven by explosive interaction between magma, magmatic gases, and groundwater. Calderas are large volcanic craters formed by an explosive volcanic eruption or collapse of surface rock into an underlying and receded magma chamber.

The Tintic pebble dike (Figure 3) is in the Tintic epithermal gold camp in central Utah, United States (Lovering, 1949). The pebbles are mainly quartzite. Open (matrix supported) versus closed (fragment supported) textures (Figure 3a) might be related to energy and/or velocity of emplacement. Some of these pebbles have 'onion skin' spalled rims, which might be related to shatter cleavage because some quartz grains within the quartzite pebbles are intensively patterned with deformation lamellae (Figure 3b) that might reflect explosive formation and emplacement. The matrix in Tintic breccia is mainly comminuted (ground-up) rock flour.



a) b)

Figure 3. Tintic pebble dike is a classic hydrothermal breccia.

The Tintic pebble dike is in the Tintic epithermal gold camp, central Utah, United States (Lovering, 1949). **a)** The pebbles are mainly quartzite, and the matrix is mainly comminuted (ground-up) rock flour. **b)** quartz grains within the quartzite pebbles are intensively patterned with deformation lamellae (right: central grain is about 4 millimetres long) that reflect explosive formation and emplacement.

Large, economic epithermal deposits are often characterized by multiple stages of brecciation and mineralization. Consequently, key characteristics that indicate mineralization and multiple mineralizing events in hydrothermal breccias in the epithermal environment should be looked for. These include a) black, sulfide-rich matrix, b) silicified and mineralized matrix, c) quartz vein fragments (especially mineralized ones), and e) breccia fragments (especially those mineralized with quartz and/or sulfide. These features are equally significant in breccias associated with porphyry deposits.

Definitions of breccia, breccia pipes, hydrothermal breccia, collapse breccia, fault breccia, pseudobreccia or crackle breccia, and sedimentary breccias and conglomerate.

Breccia in the porphyry and epithermal deposit environmenta (aside from sedimentary breccia, below) is a coarse-grained clastic rock composed of rotated and/or inflated clasts or fragments that are typically angular or rounded, held together by a relatively fine-grained matrix (cf. Sawkins and Sillitoe, 1985). Breccia can be named after the matrix composition, for example, *tourmalinite breccia* (tourmaline-quartz matrix), or *magnetite breccia* (magnetite-apatite matrix). Alternative qualifiers refer to process of formation, such as *hydrothermal breccia* (formed by rupturing due to hydrothermal explosion), *collapse breccia* (from stoping triggered by the corrosive action of hydrothermal fluids or by magma withdrawal), *magmatic breccia* (formed by rupture related to the intrusion of a magma melt or crystal mush with variable hydrous component), and *fault breccia* (fragmentation results from frictional breaking and/or rock bursting in dilatant fractures). Detailed descriptions of breccia clasts and breccia matrix are essential, especially if either or both are mineralized/altered. Maximum fragment size, modal fragment size and *open* (matrix-supported) or *closed* (fragment-supported) framework, can be related emplacement energy. As a rule of thumb, if the percentage of fragments on a planar surface is less than 50%, the breccia is likely *open*, or matrix supported. Breccia and porphyry commonly are genetically related.

Breccia pipes, also referred to as diatremes or chimneys, are masses of breccia with an irregular cylindrical shape that intrude and crosscut earlier rocks. Diatreme (Doubrée, 1891) means 'through the hole' and implies emplacement by a drilling process that used the explosive energy of gas-charged magmas (cf. Bryant, 1968, and Bryner, 1968). Most breccia pipes are formed by an explosive mechanism accompanied by gas fluxing and fluidization (Reynolds, 1954; Richard and Courtright, 1958; Carr, 1960), rock bursting, stope cave filling (Locke, 1926; Gates, 1959; Perry, 1961; Norton and Cathles, 1973) and rounding of fragments by attrition due to movement during emplacement (Clark, 1990). Shatter cleavage is an 'index fossil' for breccia because it occurs close to, or adjacent to, some breccias (see insert *Story on 'index fossil' shatter cleavage* and Godwin, 1973, 1975 and 1976).

Hydrothermal breccia is formed by rupturing due to hydrothermal explosion and subsequent emplacement (cf. Burnham, 1979 and 1985).

Collapse breccia is formed by volume reduction by processes such as magma withdrawal (cf. Perry, 1961), and dissolution by hydrothermal-related processes.

Fault breccia is formed by rupture due to faulting. Fragmentation is primarily a result of frictional breaking and/or rock bursting into dilatant zones.

Pseudobreccia or crackle breccia are commonly used terms but should be avoided. Pseudobreccia or crackle breccia describes a rock with a fragmental appearance due to alteration and/or veining in or around closely spaced fractures. However, there is no fragment rotation or fragment inflation by the intrusion of a matrix. Better names for 'pseudobreccia' or 'crackle breccia' would be 'altered crackle zone' or 'altered fracture zone' because the demonstration of fragment rotation and fragment dilation (inflation) by an intruded matrix, is essential to the definition of a breccia.

Sedimentary breccias and conglomerates are distinct from, but sometimes confused with, hydrothermal breccias of specific interest in porphyry and epithermal deposits. These two types can often be distinguished by careful examination of the matrix and fragments; specifically, mineralized/altered matrix or fragments indicates a hydrothermal origin.

Hydrothermal breccias and related fracturing are attractive sites for precious-metal mineralization in epithermal deposits because a) the fragmented rock and related fractures provide structurally permeable zones favouring precipitation of precious-metal–bearing minerals, b) adiabatic expansion related to brecciation results in solution cooling, saturation and selective vapour loss leading to precipitation of precious-metal minerals, c) the interaction of magmatic water and groundwater—both of which might bear precious metals—leads to the precipitation of precious-metal minerals, and d) they can host bonanza precious-metal grades (see inserts *Story about the small breccia outcrop responsible for discovery of Sleeper Gold Mine, Nevada, United States* and *Story of the mining history of an epithermal silver deposit at Pachuca, Mexico*). Particularly important features are a) adiabatic expansion, with attendant cooling, solution saturation and selective vapour loss causing precipitation of gold (see insert *Explanation of why angel wing texture is associated with gold mineralization*); b) black matrix breccias that often result from fine-grained sulfides (such as pyrite) that can entrap and host gold, in part because the sulfur in the sulfides destabilize gold transport in gold-bearing thio-complexes, and c) episodic crack-seal resulting in multiple silicification and brecciation events (identified by the occurrence of vein or breccia fragments within a breccia, each of which is a potentially a precious-metal mineralizing event).

Story about the small discovery outcrop of breccia at the Sleeper Gold Mine, Nevada, United States.

Figure 4. Discovery outcrop at the Sleeper epithermal gold mine, central Nevada, United States.

Although obscured by overlying gravel, the outcrop in Figure 4 is breccia. It is not a spectacular looking outcrop. However, because it had significant gold values it led to the discovery of the Sleeper gold mine that is generally deeply covered by overburden. The importance of breccia cannot be overstated.

Story of the mining history of an epithermal silver deposit at Pachuca,Mexico.

Dreier (2016), notes that in the 500-year mining history of epithermal deposits at Pachuca, Mexico, there has been economically cyclical years of prosperity. Mining in breccia pipes (chimneys) were marked by bonanza profits, but these events were followed by decades of poverty. When the high-grade pipes were mined out, operators limped along, mining low-grade veins between these pipes. Thus, the identification and definition of zoning in epithermal silver-gold districts is a key to locating bonanza breccia pipes and their associated high-grade orebodies. This history of boom and bust is common to many epithermal mines.

Carlin-type gold deposits are commonly hosted in black carbonaceous limestones that are often phosphatic, as indicated by associated green variscite. Dikes, possibly representing larger intrusions at depth, appear to be important. These dikes are often volumetrically insignificant within the deposit but appear to be the main avenues for the introduction of precious metals into the deposits.

Dilatant Structures Related to Regional and Local Faults

Dilatational structures in brittle faults relate to how these faults form, develop, and evolve as fluid flow conduits for epithermal deposits. Because these structures occur at relatively shallow levels and in brittle volcanic rocks, they tend to be erratically discontinuous. Consequently, very detailed prospecting and mapping (at the surface and at depth by drilling) is often required to define orebodies. Because hydrothermal fluids need open structures for access, structural studies can be key exploration guides. Multistage fracturing and structural system size matters because large, complex systems can yield large districts. Conversely, smaller, and simpler systems are less likely to generate large deposits.

Dilatant zones at a regional scale are important sites for epithermal deposits. Pull-apart basins, illustrated in Figure 5, are important target areas. Such basins can be marked by younger sedimentary rock infills. Structures related to maars can be particularly important because they are genetically related to volcanic-thermal events, which can also be related to mineralization.

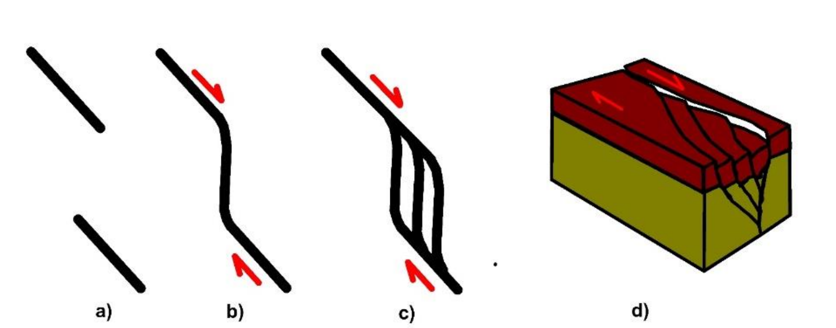


Figure 5. Development of pull-apart basins (kilometres across) are regionally positive for epithermal deposits.
*The sequentially imbricated faults generated in **a)** to **c)** reflect the theme of fault dilation demonstrated in Figure 7, but at a regional rather than a local scale. Dilated zones related to the central curved faults in **b)** to **d)** are particularly likely to be markedly dilatant. The fault structures are complicated but occur in predictable orientations. The example in **d)** illustrates dropping fault blocks and is called a 'negative flower structure'; the reverse can happen and is called a 'positive flower structure'.*

Pull-apart, concentric, radial, and caldera-related structural features can sometimes be identified by lineament analysis of air photos, satellite and light detection and ranging images (LIDAR). The patterns represented in Figure 6 can be apparent on such images. This figure is an interpretation of an aerial photograph that indicates, from radial and concentric lineaments, a possible caldera-like circular feature about 12 kilometres in diameter. The main mine in this area is marked in purple as 'Camp, mill & adit' and is within the circular structure. The presence of the caldera-like geometry in this interpretation was not apparent on regional- or property-scale geological mapping. Structural patterns can be important to epithermal deposit discovery.

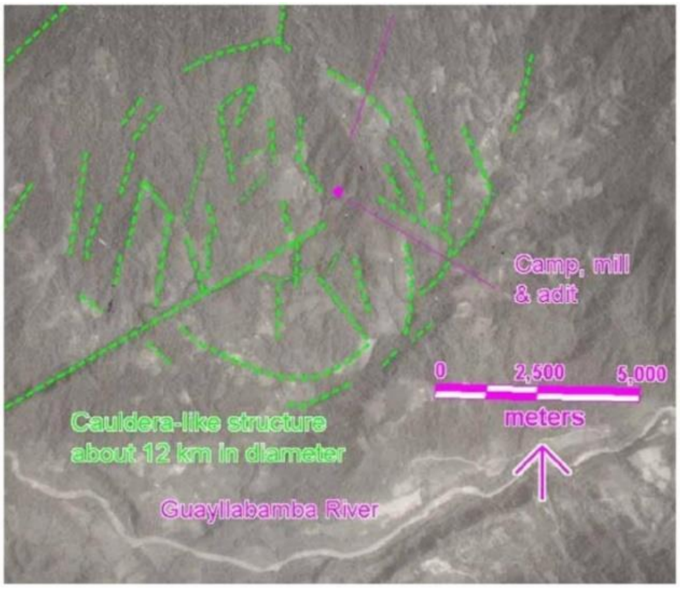


Figure 6. Aerial photograph with caldera-like lineaments, El Corazon gold property, Ecuador.

Dilations resulting from local fault zone movement also favour deposition of veins when they become channels for mineralizing hydrothermal fluids. Consequently, fault intersections and/or bends in faults can lead to dilations that can be filled by vein materials. Specifically:

- **dilations at major fault intersections** can become locations of important ore deposits by providing chimney-like, structurally permeable zones. The chimneys can persist to depth; consequently, they can facilitate hydrothermal flow from source to surface. Such hydrothermal chimneys can develop wide veins, high vein densities, maximum vertical ore intervals and high ore grades.

Dilations at bends in faults that favour fluid flow and vein formation are sketched in Figure 7. Understanding fault movements can identify focal points for exploration. Note that the orientation of the faults does not have to be vertical as shown in Figure 7; however, orebodies in normal faults tend to form openings where the faults steepen when they cut relatively hard rocks, and close where they flatten when they cut relatively softer rocks—especially within 500 to 600 metres of the paleosurface, where the confining pressure becomes insufficient to maintain a shear plane.

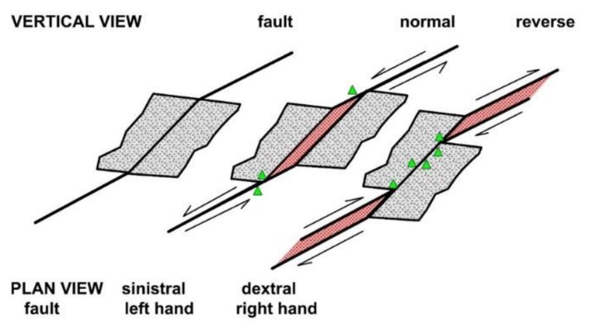


Figure 7. Structural features that enhance possibilities of dilatant zones suitable for epithermal vein mineralization.
Vertical and plan views are presented but the orientation can be in any position. The scale of a dilatant zone can vary from metres to hundreds of metres. The grey, speckled rock unit is more competent than surrounding rock, causing fault deflection (like light bending toward the normal direction in more resistant [refractive] rock). Dilatant ore zones are illustrated in red, and the green triangles represent brecciated areas.

Orebody shapes and locations can often be predicted given known fault geometries. Fault geometry can be identified by field mapping. Detailed movements can also sometimes be determined by separately mapping the topography of hanging wall and footwall from detailed drillhole or underground information and moving the acquired topography so that hanging wall and footwall topographies match. This type of analysis can sometimes predict the location of additional dilatant zones of possible significance.

Chemical and Physical Constraints to Mineral Deposition in Epithermal Deposits

Fundamental chemical and physical constraints related to epithermal deposits, addressed below, are:

- coupled oxidation–reduction reactions,
- destabilization of sulfurous gold thio-complexes that precipitates pyrite and gold,
- chemical constraints on alteration mineralogy and
- physical constraints on upwardly moving hydrothermal fluids.

Coupled oxidation-reduction reactions transfer and balance electrons. One substance is oxidized by losing electrons, and a second is reduced by gaining electrons. (There is an old mnemonic, 'LEO the lion says GER': Loss of Electrons is Oxidation; Gain of Electrons is Reduction.) Reactions of this sort, which are significant to the precipitation of gold (and silver) in epithermal deposits, relate to the coupled oxidation of carbon in clastic rocks and limestone. EQUATIONS 1 to 4 illustrate precipitation and reduction of gold by concomitant oxidation of carbon. The importance of carbonaceous trash or graphitic and carbon components in host rocks to epithermal deposits is clearly important. This is well known with respect to the formation of uranium deposits, and it is similarly relevant to gold occurrence in Carlin-type precious metal deposits.

EQUATIONS 1 to 4 represents balanced reduction and oxidation reactions, with the balanced addition and subtraction of electrons in a hydrothermal fluid. This coupled oxidation-reduction with a hydrothermal fluid in EQUATION 4 results in a) the precipitation of native gold, b) the conversion of carbon to carbon-dioxide, and c) the generation of hydrochloric acid. Notably, the generation of acid in the carbonate host rock to Carlin-type deposits contributes to the characteristically associated decalcification and collapse breccias (see below for the model of Carlin-type deposit formation [Figure 35 in *Introduction to Carlin-Type Deposits*]). Precipitation of uranium and gold, formed in this manner, is illustrated in Figure 8 in the insert *Associations among carbon trash, uranium and gold at Bald Mountain Wash, central Nevada, United States*, and in the argument, presented below, about the origin of Carlin-type deposits.

EQUATION 1: Half-cell reaction for reduction of gold.

Au^+ = gold ion. e^- = electron. Au^0 = native gold.

$$4Au^+ + 4e^- \rightarrow 4Au^0$$

EQUATION 2: Half-cell reaction for oxidation of carbon.

C^0 = carbon. C^{4+} = carbon ion. e^- = electron.

$$C^0 \rightarrow + C^{4+} + 4e^-$$

EQUATION 3: Coupling reduction (EQUATION 1) and oxidation (EQUATION 2).

Au^+ = gold ion. C^0 = carbon. Au^0 = native gold. C^{4+} = carbon ion. Note electron balance.

$$4Au^+ + C^0 \rightarrow 4Au^0 + C^{4+}$$

EQUATION 4: Modifying EQUATION 3 to represent a hydrothermal fluid.

$AuCl^-$ = gold chloride. H_2O = water. C^0 = carbon. Au^0 = native gold. CO_2 = carbon dioxide. HCl = hydrochloric acid.

$$4AuCl^- + 2H_2O + C^0 \rightarrow 4Au^0 + CO_2 + 4HCl$$

Associations among carbon trash, uranium and gold at Bald Mountain Wash, central Nevada, United States.

A small, disseminated gold occurrence was found in trenches and drilling at Bald Mountain Wash, central Nevada (BM in Figure 34). It was originally found during follow-up on a NURE (National Uranium Resource Evaluation regional geochemical survey by the United States Geological Survey) stream-sediment anomaly for uranium. Gold on this property occurs in a tuffaceous unit that has abundant black carbonaceous fragments (Figure 8a). Where the gold-uranium mineralization occurs, the black fragments are bleached and sometimes difficult to define (Figure 8b). The implication is that the gold, as is commonly documented for uranium, is precipitated by a coupled oxidation-reduction reaction. The carbon is oxidized (the fragments change from black to pale tan) and the uranium and gold are reduced and precipitated.

a) *b)*

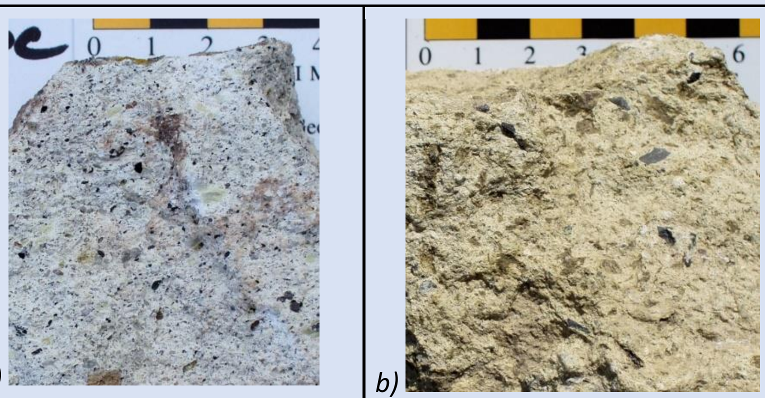


Figure 8. Unmineralized (a) and mineralized (b) tuff from Bald Mountain Wash, Nevada, United States.
a) *In the unmineralized tuff the plant fragments are black and relatively unaltered. In* ***b)*** *the plant fragments are bleached tan by alteration and mineralization with uranium and gold. The Bald Mountain Wash prospect is labeled BM in Figure 34.*

Destabilization of sulfurous gold thio-complexes that precipitates pyrite and gold is outlined in EQUATIONS 5 to 7. The generation of pyrite with native gold (EQUATION 7) is a result of reactions that move to the right because of destabilization of the gold thio-complex by evolution of hydrogen sulfide (especially during boiling) and the combination of sulfur with iron. This explains a) the common association of gold with iron-bearing sulfides (e.g., pyrite and arsenopyrite), b) the need to have a source for the iron for the sulfides (e.g., mafic andesite can be a more favourable host to gold mineralization than a felsic rhyolite), and c) the importance of paying attention to sulfide distribution during exploration for epithermal deposits.

EQUATION 5: Destabilization of gold thio-complex to form native gold and hydrogen sulfide gas.

$Au(HS)^{2-}$ = gold-thio-complex. H^+ = hydrogen ion. Au^0 = native gold. H_2S = hydrogen sulfide gas.

$$2Au(HS)^{2-} + 2H^+ \rightarrow 2Au^0 + 2H_2S$$

EQUATION 6: Half-cell reaction for oxidation of carbon.

The iron is mainly from ferromagnesian minerals, magnetite or other iron minerals.

H_2S = hydrogen sulfide. FeO = iron oxide. FeS_2 = pyrite. H_2O = water. H^+ = hydrogen ion.

$$2H_2S + FeO \rightarrow FeS_2 + H_2O + 2H^+$$

EQUATION 7: Combination of EQUATIONS 5 and 6 resulting in native gold associated with pyrite.

$Au(HS)^{2-}$ = gold-thio-complex. FeO = iron oxide. Au^0 = native gold. FeS_2 = pyrite. H_2O = water.

$$2Au(HS)^{2-} + FeO \rightarrow 2Au^o + FeS_2 + H2O$$

Aqueous fluids forming epithermal deposits typically precipitate their metals at temperatures between 150 and 350°C. Gold is transported most commonly in thio-complexes (e.g., $Au(HS)_2^-$), but also in chloride complexes (e.g., $AuCl^-$). Economic epithermal deposits require fluids with anomalous concentrations of precious metals (gold and silver) and elements with which they might form complexes, which include Hg, As, Sb, Bi, Tl, Se, Te, Li, Ba, B and F. Deep water in the surrounding rock is approximately in equilibrium with minerals such as quartz, K-feldspar and plagioclase. Therefore, at the pressures and temperatures found at depth, the water will be saturated with elements such as silica, potassium and calcium. As this water approaches the surface, three main processes may change the character of alteration and cause precipitation and changes related to changes in alteration facies. These processes are a) temperature drop, b) degassing of CO_2 accelerated by boiling, and c) removal of sulfur by degassing/boiling or by precipitation of minerals containing sulfur.

Chemical constraints on alteration mineralogy are mainly those explained by the T versus m_{KCl}/m_{HCl} plot in Figure 9a and EQUATIONS 8 and 9 (after Myer and Hemley, 1967). These equations provide the framework for understanding sequences of alteration minerals in zoning within porphyry and epithermal deposits. Note that these equations are the same as those relevant to porphyry deposits, however, the temperatures involved in epithermal deposits are lower and the K-felspar is adularia rather than orthoclase (Figure 9a, paths D and E). EQUATIONS 8 and 9 and the alteration stability diagram in Figure 9a show that mineral stability of feldspars, micas and clays are commonly controlled by hydrolysis (where K^+, Na^+, Ca^{2+}, Mg^{2+} and other cations are transferred from the mineral to the solution and H^+ enters the solid phase). This is the case for both porphyry and epithermal deposits. As a result, similarities can be expected in zoning patterns between porphyry and epithermal deposits.

EQUATION 8: Equilibrium between adularia and muscovite.

$KAlSi_3O_8$ = adularia. H^+ = hydrogen ion. $KAl_3Si_3O_{10}(OH)_2$ = muscovite. SiO_2 = quartz. K^+ = potassium ion.

$$3KAlSi_3O_8 + 2H+ \leftrightarrow KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$$

EQUATION 9: Equilibrium between muscovite and kaolinite.

$KAl_3Si_3O_{10}(OH)_2$ = muscovite. H^+ = hydrogen ion. H_2O = water. $Al_2Si_2O_5(OH)_4$ = kaolinite. K^+ = potassium ion.

$$4KAl_3Si_3O_{10}(OH)_2 + 2H+ \leftrightarrow H_2O + 6Al_2Si2O_5(OH)_4 + 4K^+$$

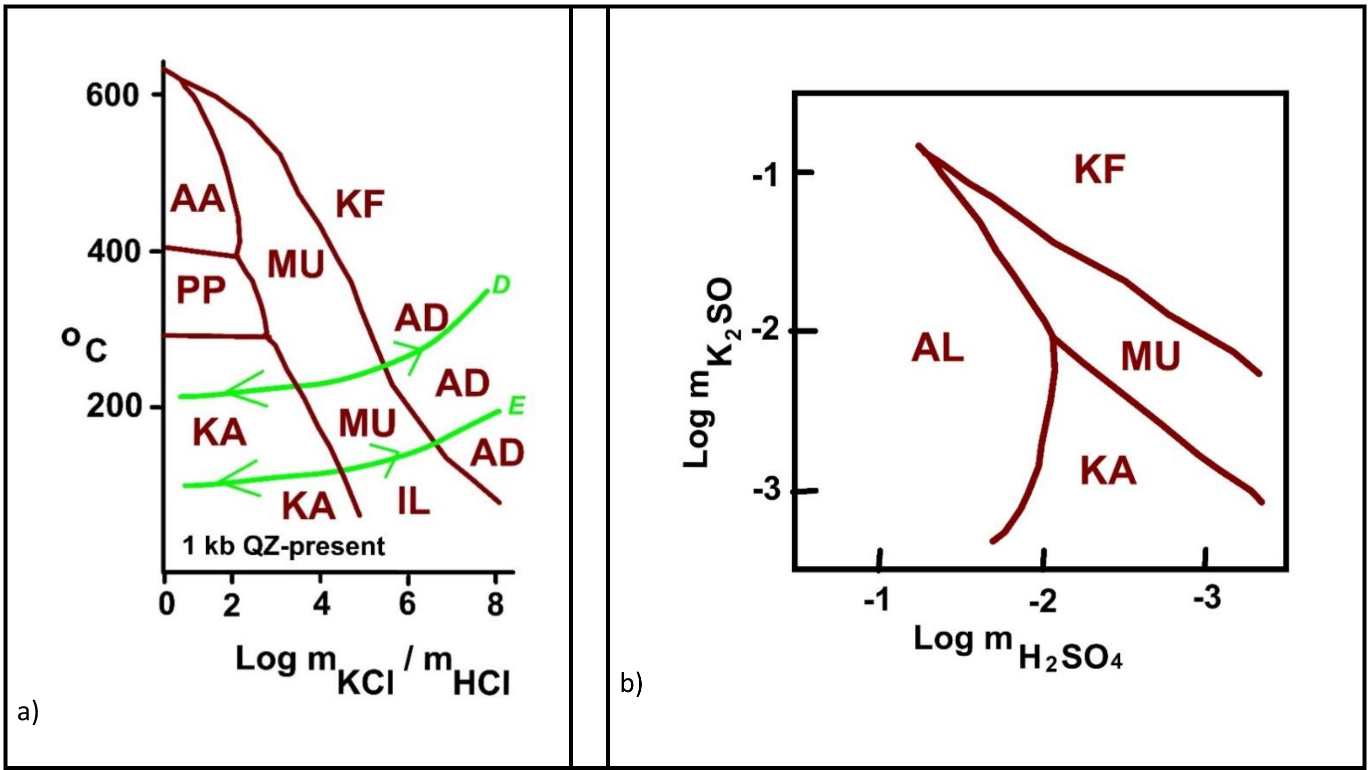


Figure 9. Plots of basic phase diagrams of a) T versus m_{KCl}/m_{HCl}, and b) log m_{H2SO4} versus log m_{K2SO4} related to alteration in the epithermal environment.
a) *Paths D and E represent decreasing temperature paths in the epithermal environment, either cooling with movement away from a magmatic heat source (left direction) or heating with movement toward one (right direction). On the left side of the T versus m_{KCl}/m_{HCl} plot, the K-content is low, but the water (and mobilization of calcium and sodium from plagioclase destruction) promotes alteration and hydration of rock minerals to generate propylitic alteration assemblages (diagram is after Myer and Hemley, 1967).* ***b)*** *The log m_{H2SO4} versus log m_{K2SO4} plot shows the stability of alunite in an acidic, sulfate-rich environment (diagram is after Rose and Burt, 1979). m_{KCl}, m_{HCl}, m_{H2SO4} and m_{K2SO4} = molar concentrations of potassium chloride, hydrochloric acid, sulfuric acid, and potassium sulfate, respectively. Abbreviations:* ***AA*** *= andalusite,* ***AD*** *= adularia (K-feldspar),* ***AL*** *= alunite,* ***IL*** *= illite,* ***KA*** *= kaolinite,* ***KF*** *= orthoclase (K-feldspar),* ***MU*** *= muscovite (sericite),* ***PP*** *= pyrophyllite and* ***QZ*** *= quartz.*

Alunite stability (Figure 9b), after Rose and Burt (1979), depends on the activity of sulfate (SO_4^{2-}) as well as the ratio of cations H^+ and K^+. Strongly acidic environments, especially if rich in sulfuric acid, favour alunite formation (cf. Butler and Gale, 1912). Sulfurous acidic environments can be generated from exhalations from intrusive rocks (i.e., hypogene) or from surface oxidation of sulfides, such as pyrite or steam-heated sinter (i.e., supergene). Distinction of hypogene from supergene alunite can be difficult, but mapping can help. Hypogene alunite, commonly pink, can be spatially related to causative veins. Supergene alunite, generally white, can occur at paleosurfaces and in sinters where it might be associated with steam-generated native sulfur. Alunite is a sulfate; therefore, a field sulfate zap test can help with identification (Godwin, 2020).

Iron or manganese carbonates and sulfides, such as siderite, rhodochrosite and pyrite, are common gangue minerals in epithermal veins. They are of special interest because precipitation of carbonate might be a result of the degassing of CO_2, which would also be accompanied by the degassing of SO_2 with the same consequences as discussed with thio-complex destabilization (EQUATIONS 5 to 7) and angel wing habit, below.

Sulfates such as barite, gypsum and alunite are less common gangue minerals in epithermal alteration. Sulfates might be a result of the degassing of SO_2, which would also be accompanied by the degassing of CO_2 with the same consequences as discussed with thio-complex destabilization (EQUATIONS 5 to 7) and angel wing texture, below.

Relatively iron-rich host rocks, all other factors being equal, frequently support better gold grades because the iron in the host rock can combine with sulfur in the hydrothermal fluid to form iron-bearing sulfides like pyrite and/or arsenopyrite. These minerals sequester sulfur; therefore, they can entrain gold that can no longer be transported as sulfur-bearing thio-complexes, as explained by EQUATIONS 5 to7.

Carbonaceous host rocks facilitate entrapment of precious metals by the coupled oxidation-reduction mechanism described in EQUATIONS 1 to 4. In addition, the generation of acid as a by-product of coupled oxidation-reduction can contribute to the characteristically associated decalcification and collapse breccias in the carbonate host rock of Carlin-type deposits (refer to model of Carlin-type deposit formation below).

Physical constraints on upwardly moving hydrothermal fluids include permeable and porous host rocks, aquicludes, cooling, boiling and condensation. The mechanisms and significance of these features are elaborated on below.

Permeable and porous host rocks allow access to hydrothermal fluids that are commonly introduced from fault systems. Where precious metals are precipitated from the hydrothermal fluids, orebodies can be formed. These units can be particularly productive if they contain an efficient trapping mechanism that facilitates precious metal precipitation, such as a carbonaceous-rich and/or an iron-rich component (refer to EQUATIONS 1 to 7).

Aquicludes or aquitards are impermeable or low-permeability rock strata. Aquicludes can a) stop hydrothermal fluid flow, b) guide hydrothermal fluids toward or through more permeable units or into faults and thrust planes, and c) force underlying hydrothermal systems to spread laterally.

The cooling of hydrothermal fluid results in supersaturation and precipitation of silica (e.g., quartz, opal, chalcedony). If the system is at a high temperature, feldspars will be sericitized (see Figure 9a, from about 200 to 300°centigrade); however, at less than 150°centigrade the alteration of feldspar will be to montmorillonite (smectite) or illite.

Temperature and pressure changes during the upward migration of hydrothermal fluids are illustrated in Figure 10 (after Barton and Toulmin, 1966). Temperature decrease is largely a result of a) reversible cooling (modeled as slow entropy change), b) irreversible cooling (modeled as rapid, adiabatic expansion through a throttle or choke zone), and c) cooling from groundwater mixing. These different processes are important because changes in pressure, temperature and salinities can be related to mineral precipitation. However, of particular significance is throttling, related to a type of boiling, where sudden expansion through a restriction results in a rapid drop in pressure and temperature. The sudden drop in pressure and temperature is sometimes related to high precious-metal grades, and is particularly applicable to, and emphasized in, the classic Buchanan epithermal deposit model described in a later section.

Boiling is one of the more important triggers for precious-metal deposition in epithermal deposits. This is because boiling selectively removes volatiles leading to saturation and temperature decrease—both of which favour mineral deposition. The most important gas separations in a boiling hydrothermal fluid are preferentially reduced components (H_2 > CH_4 > H_2S) greater than oxidized components (CO_2 > SO_4^- > SO_2). In an open system, boiling with gas separation occurs at a constant temperature. In a closed system with adiabatic expansion (cf. throttling or irreversible cooling) of the separated gas, the temperature decreases. Of critical significance is the degassing of CO_2 and H_2S (also H_2, HS^-, SO_4^{2-}) from the liquid phase because as these volatiles escape the remaining fluid tends to increase in pH (removal of CO_2 and H_2S species) and the m_{KCl}/m_{HCl} ratio also increases (Figure 9a; by removal of H_2 and H_2S).

The removal of carbon dioxide (CO_2) promotes precipitation of calcium carbonate, specifically calcite (also rhodochrosite, siderite, etc.) in the 'index fossil' angel wing texture, and travertine in deposits around hot springs. It is formed from geothermally heated supersaturated alkaline waters, which degas CO_2 upon boiling or surface emergence. This results in an increase in pH, causing the precipitation of carbonate, which can be replaced pseudomorphically by quartz, resulting in formation of the 'index fossil' angel wing texture.

The removal of hydrogen (H_2 and H_2S) causes precipitation of K-feldspar, in this case adularia, by isothermally moving the system in Figure 9a and EQUATIONS 8 and 9 to the right, into the field of K-feldspar (**AD**). In addition, the degassing of sulfur (H_2S) results in destabilization of gold thio-complexes (e.g., $Au[HS_2]$; see EQUATIONS 5 to 7). Since the gold can no longer be transported as a sulfur complex, it is precipitated. Thus, boiling associated with a sustained flux of metal-rich hydrothermal fluids favours epithermal ore formation and the development of large and/or bonanza precious-metal deposits. Of course, concentration of precious metals in the hydrothermal fluid and volume and duration of the flow are strong determiners of the amount and grade of ore mineralization produced.

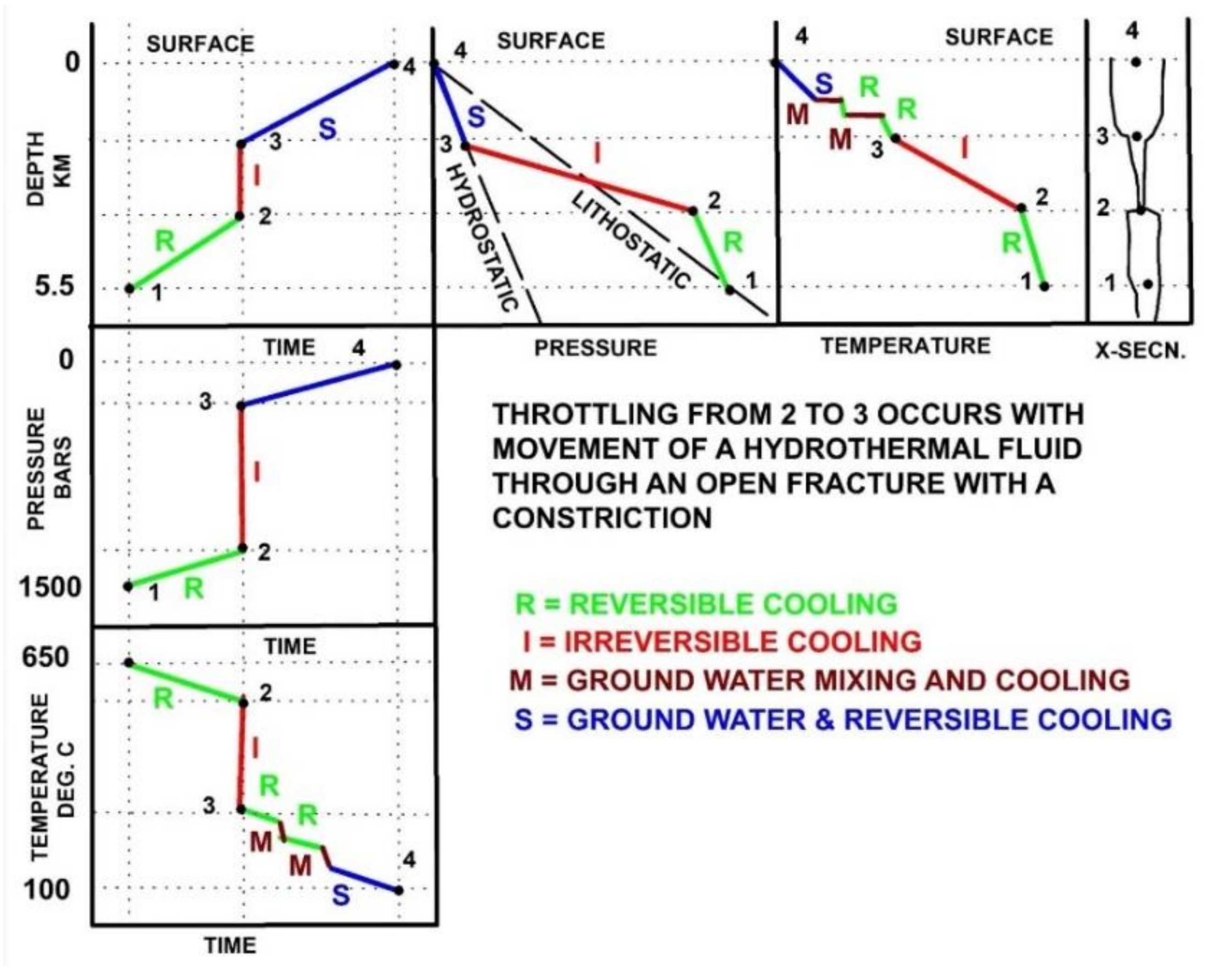


Figure 10. Model for cooling of upwardly moving hydrothermal fluids in an epithermal deposit environment. Cooling, pressure changes and salinity changes (e.g., especially near surface groundwater mixing [3 to 4]) are related to mineral precipitation. Irreversible cooling (throttling; 2 to 3), a type of boiling related to bonanza mineralization in the Buchanan model results in a sudden decrease in temperature and pressure. The figure is after Barton and Toulmin (1966).

Boiled and cooled hydrothermal fluids in the epithermal environment are strongly depleted in elements such as silver, gold, and tellurides, resulting in deposition of native silver and gold and gold-silver tellurides. By comparison, arsenic, manganese, antimony, and zinc are less depleted and precipitate at different locations, commonly peripherally or at depth, as minerals that include arsenopyrite, rhodochrosite, sulfosalts (e.g., tetrahedrite) and sphalerite.

Condensation of steam, for example vapour boiled from the water table, will reside in larger pores and channels, but also will tend to collect in smaller pores and channels and trickle back to the water table. This subaerial environment will tend to be strongly oxidizing; therefore, H_2S concentrated in vapour above the water table will commonly oxidize to sulfuric acid (H_2SO_4) and native sulfur (S°), producing an acidic, sulfate-rich environment. This environment commonly gives rise to strong argillic alteration that forms lithocap clays (cf. Figure 9a: muscovite to kaolinite corresponding to lower m_{KCl}/m_{HCl} ratios derived from reduced acid and earlier depletion in K^+). Similarly, reactions in this environment are driven to the lower left-hand corner of Figure 9b as potassium is depleted and sulfuric acid is increased. Kaolinite and alunite become the common phases near the water table. An example of such alteration occurs at Steamboat Springs, Nevada, where the cap above the water table consists of a porous, mass of opaline silica that has been extremely leached by sulfuric acid produced by the oxidation of steamed hydrogen sulfide (H_2S). Several metres below the water table, acid returns from the cap and causes a zone of alunite greater than kaolinite to overlie a zone where alunite is less than kaolinite. The alunite-kaolinite zone merges gradationally downward into background alteration characterized by pervasive montmorillonite and illite.

Seven Must-Look-For 'Index Fossils' for Precious Metal Discovery in Epithermal Deposits

Seven 'index fossils' that are key indicators of precious metal discovery in epithermal deposits are (Figures 11 to 17):

1. ginguro gold-electrum with colloform habits in veins (Figures 11 and 14b).
2. angel wing habit in quartz or carbonate veins (Figures 12).
3. adularia in veins or vugs (Figure 13).
4. black matrix hydrothermal breccias (Figures 14).
5. amethyst in veins or vugs (Figure 15).
6. gusano habit in quartz-pyrophyllite lithocap (Figure 16).
7. spongy residual-quartz lithocap (Figures 17).

The significance of these seven 'index fossils' are described below.

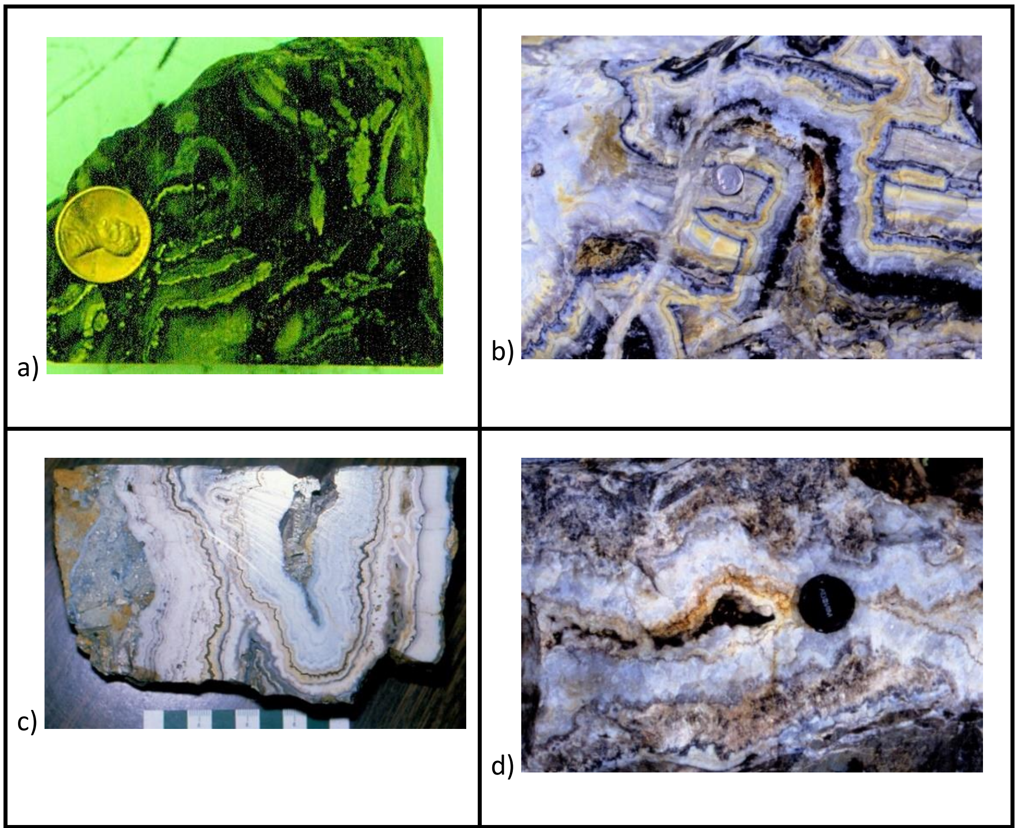


Figure 11. 'Index fossil' ginguro and associated colloform habits. *Specimens are from the Sleeper gold deposit, north-central Nevada (SL in Figure 34).* ***a)*** *Ginguro's rich gold habit with gold deposited at boundaries of colloform bands (false greenish colour from using available indoor light)—any texture that looks like ginguro habit is an obvious index fossil for precious-metal epithermal deposits. Photos b to d show typical colloform textures.* ***d)*** *Shows symmetrical colloform banding in a gold vein, formed from vein-wall margin to centre marked by a vug.*

1. Ginguro 'index fossil' with colloform and vuggy habits in veins (Figure 11) is due to the sequential deposition of quartz, and/or other minerals, in open spaces. Although these habits can be barren, most precious-metal epithermal deposits have these in abundance. Any habit that is associated with or looks like gold-electrum–rich ginguro texture (Figures 11a and 14b) is obviously an index fossil for precious-metal epithermal deposits.

2. Angel wing 'index fossil' habit in quartz or carbonate veins (Figures 12) is also uninspiringly called lattice and lamellar texture. It is generally interpreted to represent quartz replace-ment of carbonate whorls, although direct precipit-ation as quartz is a possibility. It is *diagnostic* of a hydrothermal system that was boiling or effervescing. In epithermal deposits, angel wing is commonly associated with significant gold values; hence, the good 'angel' name is commonly used to express enthusiasm for it marking gold potential. Angel wing texture is, therefore, an 'index fossil' for precious-metal epithermal deposits. (See inserts *Explanation of why angel wing texture is associated with gold mineralization*, and *Story about angel wing at the Mount Skukum mine, southwestern Yukon, Canada.*)

Explanation of why angel wing habit is associated with gold mineralization.

Angel wing texture (also boringly called lattice and lamellar texture) represents carbonate whorls or quartz replacement of these carbonate whorls; it might also be a direct precipitate of quartz. It is diagnostic of any hydrothermal system that was boiling or effervescing, where water vapour (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2) and hydrochloric acid (HCl) are preferentially degassed. Removal of water vapour increases the metal concentration in the remaining solution so that the metals may become saturated and precipitated. More specifically relevant to angel wing texture is that the release of CO_2 causes an increase in pH with the consequent precipitation of carbonate with characteristic acute angle whorls that can be subsequently replaced by quartz that pseudomorphs the carbonate with angel wing 30° symmetry. In addition, coincident degassing of SO_2 destabilizes any gold carried and complexed with sulfurous thio-species, thus also favouring gold precipitation. This texture is particularly common in low-sulfidation epithermal gold deposits. Its formation involves the following stages according to Etoh et al. (2002): a) deposition of bladed calcite, b) precipitation of fine-grained quartz (±adularia) on the surface of calcite blades, c) dissolution of calcite blades, leaving cavities in the interstices between aggregates of quartz, and d) infilling of the cavities by later quartz (i.e., pseudomorphs of the original bladed calcite). This sequence agrees with and was partially explained by Lindgren (cf. 1933). Adularia, if associated with angel wing texture, is additional support for boiling or effervescence and is another positive 'index fossil' for gold. This is because degassing of hydrogen species increases the ratio m_{KCl}/m_{HCl} so that the system moves into the K-feldspar–adularia stability field (to the right along paths D and E in Figure 9a). Angel wing and adularia formation emphasize the importance of boiling as a trigger for metal deposition in epithermal deposits.

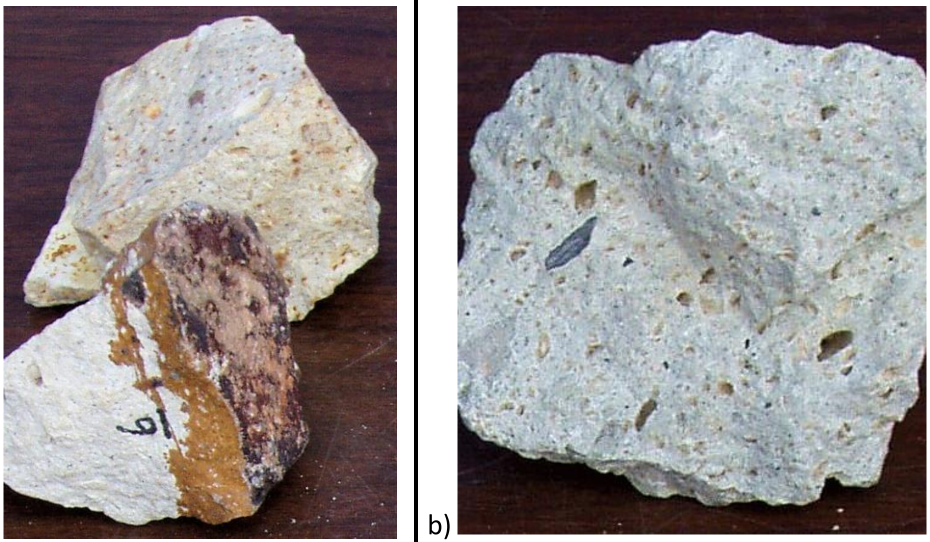
Story about angel wing at the Mount Skukum mine, southwestern Yukon, Canada.

Mount Skukum must have been trodden extensively by prospectors during and since the Yukon Gold Rush in 1898, yet the gold deposits were not discovered. Part of the reason may have been that nearby gossanous pyritic outcrops pulled attention from what turned out to be more important features. A creek near the gossanous outcrops and the main deposit carried white vein quartz float that lacked sulfides and looked like barren 'bull quartz'. However, on close inspection, the vein quartz was loaded with angel wing habit—a tip-off that the veins could be auriferous—as they were (Figure 12)! This quartz float yielded high values of gold on assay, which led to the discovery of the Mount Skukum epithermal gold mine about a century after the Yukon Gold Rush.

Figure 12. 'Index fossil' angel wing texture.
a) *Underground at the Mount Skukum gold mine in the Yukon, Canada, this vein breccia has angelwing texture that is not visible in this picture. Specimens* ***b)*** *and* ***c)*** *illustrate angel wing texture from the Bullfrog gold mine, central-western Nevada, United States (BF in Figure 34). Angel wing habit is diagnostic of boiling.*

Angel wing texture is abundant at the Bullfrog gold mine (Figures 12a, 12b and 30; BF in Figure 34) in southwestern Nevada, United States. The gold precipitated because of boiling in a vein-fault system. (This is not defined in descriptions read by the author.) The gold-bearing fluids may have been from over-pressured fluids introduced from underlying thrust detachment zones, but the precipitation of gold is in steep faults where the gold-bearing hydrothermal fluids boiled—probably as result of rapid pressure reduction—from lithostatic plus fluid pressures in the thrust detachment faults to hydrostatic in the normal faults (see model of overpressure thrust-detachment fault in a later section).

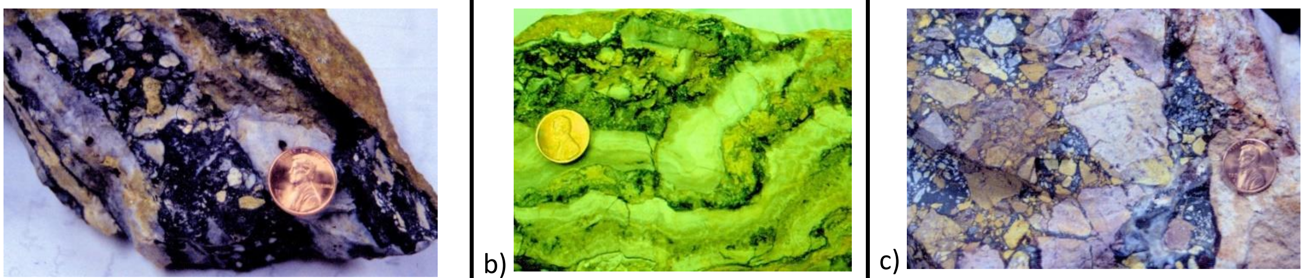
3. Adularia 'index fossil' in veins or vugs (Figure 13) in epithermal deposits is another key to gold potential. This is because adularia forms from the removal of hydrogen in vapour escaping through boiling or effervescence, which drives the fluid into the adularia stability field as the m_{KCl}/m_{HCl} increases (to the right—paths D and E in Figure 9a). At the same time, degassing of SO_2 also destabilizes gold carried as sulfurous thio-complexes, thus enhancing the probability of gold precipitation. Adularia-illite is commonly a key vector toward epithermal gold mineralization. As a result, adularia is an 'index fossil' for precious-metal–rich epithermal deposits.



a) b)

Figure 13. 'Index fossil' adularia.
These specimens of quartz-sericite-adularia tuff, all about 10 centimetres wide, are from Round Mountain in central Nevada, United States (RM in Figure 34). The adularia, which occurs as prominent wedge-shaped crystals lining small vugs, is not very visible in hand specimens but the crystals are easily recognized with the aid of a hand lens.

4. Black matrix 'index fossil' in hydrothermal breccia (Figure 14) has a black matrix generally because of fine, disseminated sulfides. This indicates the possibility that destabilization of gold-transporting sulfurous thio-complexes took place and emphasizes the importance of a black matrix over a pale matrix.



a) b) c)

Figure 14. 'Index fossil' black matrix hydrothermal breccias.
These gold-rich black matrix breccias are from the Sleeper gold mine (SL in Figure 34) in central Nevada, United States. Ginguro texture in the central photo (gold is in the band below the coin) is remarkably high grade.

5. Amethyst 'index fossil' in veins or vugs (Figure 15) has a purple colour due to replacement of silica by iron with a rare +4 valence (Kissin et al., 1993; iron generally occurs with +2 [ferrous] and +3 [ferric] valences). When +4 valence occurs in iron, it reflects extreme and rare oxidizing conditions. If gold is present in the hydrothermal solution, it can be precipitated as native gold by coupled oxidation (of iron)–reduction (of gold). Because of this, amethyst can be a key indicator of gold in epithermal deposits, and thus, is an 'index fossil' in precious-metal-rich epithermal deposits.

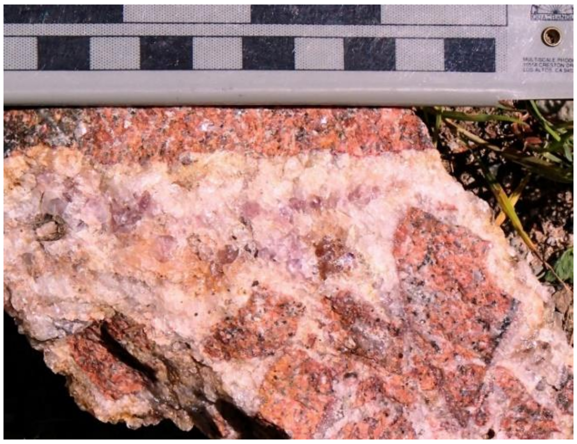
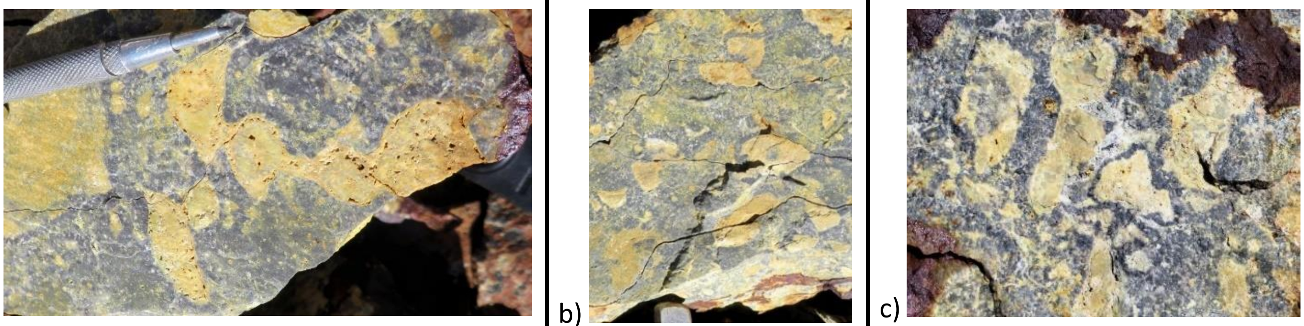


Figure 15. 'Index fossil' amethyst and vuggy quartz rims on breccia clasts.
Amethyst indicates extreme oxidation that, if a gold-bearing solution is involved, can cause precipitation of gold by coupled oxidation-reduction. It is, therefore, a key prospecting feature. The breccia, vugs and amethyst are signs of potential mineralization in the above photo. Source of the specimen is unknown.

6. Gusano 'index fossil' habit (Figure 16; *gusano* = worm in Spanish) is also called ovoidal and mottled texture (Noble et al., 2010). Gusano habit looks like worm burrows and consists of ovoid and irregularly mottled or patchy bodies several millimetres to about three centimetres in diameter (Figure 16). They are composed commonly of intermixed pyrophyllite and alunite in a fine-grained quartz or chalcedony matrix; porous pyrite ovoids also occur. Other features associated with gusano habit include silica veinlets or dikelets that are black (due to sulfides), clear or creamy. These sometimes a) are of several generations, b) host vapour cavities from microns to several millimeters in diameter and c) contain sulfides, sulfosalts, native gold, and native sulfur. Boundaries of the gusano-textured blobs are sharp against a matrix of lithocap rock. The presence of arsenic and gold indicates an exploration-significant, high-sulfidation lithocap and formation in an acidic environment. Gusano habit is also thought to commonly represent a porphyry system below the lithocap. Specifically, because pyrophyllite is a high-temperature alteration mineral, it indicates a proximal hot intrusive body. The presence of copper-bearing minerals (e.g., covellite) increases the probability of an underlying copper porphyry deposit at a depth on the order of 300 to 500 metres. Although underlying porphyry mineralization is a possibility, quartz-pyrophyllite can also occur adjacent to rhyolite domes. In epithermal lithocaps gusano habit it is an 'index fossil' for a major mineralizing system—both epithermal near the surface, and porphyry at depth.



a) b) c)

Figure 16. 'Index fossil' gusano habit (also called ovoid and mottled texture).
Ovoids commonly consist mainly of pyrophyllite and alunite. This habit indicates a high-sulfidation epithermal environment, and sometimes, an underlying porphyry deposit (see insert Origin of gusano habit). Photos were taken by John Bradford in 2015 at the Tanzilla epithermal-porphyry deposit prospect, northwestern British Columbia, Canada.

7. Spongy quartz residual lithocap 'index fossil' (Figure 17) is marked by a quartz-only rock that has been left behind when the acid conditions are so extreme that everything, including generally resistant alumina, is leached, and removed. The acid can have a hypogene hydrothermal source, or it can be a result of supergene acid generated from rocks with an exceptionally high pyrite content. Textures can be spongy quartz or granular-massive-spongy quartz. Such quartz rock is highly porous and full of boxy cavities, some rimmed or laced with quartz; opaline silica also can occur. This massive, granular quartz rock does not preserve the textures of the original rock, but local mobility of silica can result in pseudo-bedded appearances. It marks a lithocap, which can represent current surface weathering or past unconformity surfaces. It can rarely be gold bearing.

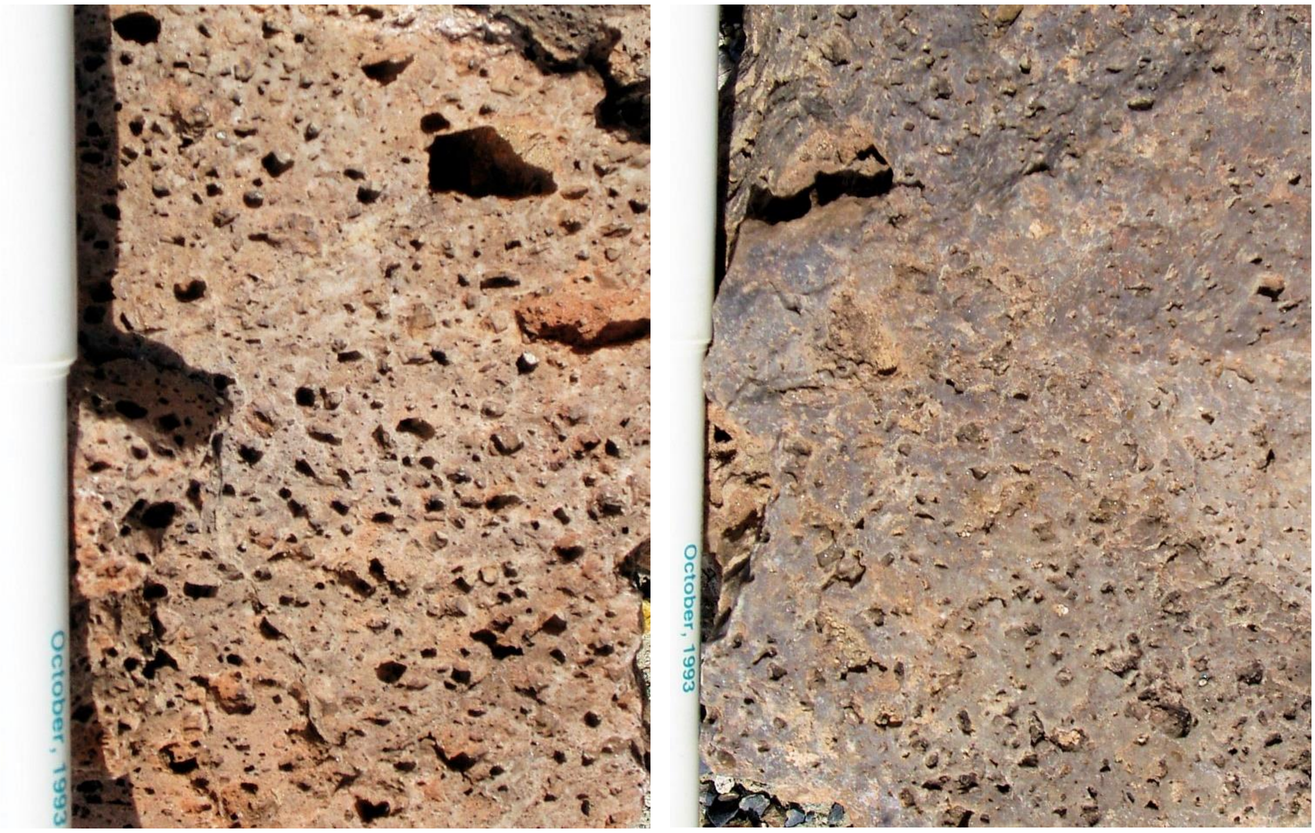


Figure 17. 'Index fossil' spongy quartz residual lithocap.
This type of lithocap consists entirely of spongy, quartz left after extreme acid leaching. Width of each photo is about 10 centimetres. Specimens are from the Goldfields area, southwestern Nevada, United States, which is characterized by high-sulfidation epithermal gold deposits (GF in Figure 34).

Be sure you understand from this section, what are the:

- **commonly associated host rocks,**
- **important structural controls,**
- **basic theoretical chemical and physical constraints, and**
- **seven must-look-for 'index fossils' for epithermal deposits.**

CLASSIC ALTERATION ZONES IN EPITHERMAL DEPOSITS

In this section on epithermal deposits, you will learn about

- ➔ **generalized lithocap alteration zones, and**
- ➔ **generalized hypogene zones.**

Classic alteration facies and their zonation specific to epithermal deposits provide important vectors to potential ore location. TABLES 2 and 3 describe the mineralogy of generalized, classical zones of lithocap and hypogene alteration in epithermal deposits (see insert *Definitions of lithocap and hypogene alteration in epithermal deposits* and *Caution regarding supergene versus hypogene origin for spongy silica, clay, alunite and illite*), including physical and chemical features that define the alteration facies and some specific features. Because wallrock alteration patterns of epithermal vein systems are similar to modern geothermal systems, temperature estimates of alteration facies that correspond to geothermal systems are also included in TABLE 2 (based on Dreier, 2016).

Definitions of lithocap and hypogene alteration in epithermal deposits.

Lithocap refers to near-surface-altered or deposited rocks that include sinter deposits, steam-heated and altered rocks and rocks with advanced argillic alteration characterized by residual quartz and quartz alunite. This residual quartz and advanced argillic alteration forms from leaching by acidic condensates from the cooling of ascending volcanic vapours. Generally, lithocap forms above the water table; however, water table levels vary with changes in paleo topography and paleoclimate, resulting in complexities.

Hypogene alteration and mineralization in epithermal deposits is a result of ascending hydrothermal fluids. Hypogene alteration generally occurs at depth but it can also ascend to overprint earlier lithocap alteration. For example, hypogene fluids associated with phyllic alteration can ascend into a lithocap and deposit sulfosalts (e.g., enargite) accompanied by gold.

Caution regarding supergene versus hypogene origin for spongy silica, clay, alunite and illite.

Spongy silica is the remnant silica left behind when the acid conditions are so extreme that everything, including generally resistant alumina, is leached, and removed. The acid can have a hypogene hydrothermal source leading to acidic condensates or can be supergene, generated from rocks with a high pyrite content. Textures of spongy silica can vary from boxy cavities with silica webs to granular quartz. Original rock textures are destroyed but local mobility of the silica can result in pseudo-bedding appearances.

Clay, alunite and illite alteration also require caution because they can be caused by hypogene and supergene processes. Pyrite weathering is acidic and can alter rock to clay and alunite; illite in volcanic rocks can be due to tropical weathering. Hypogene alunite is commonly pink, but it also can be white or tan. Supergene alunite is to be suspected with occurrence in the lithocap. Field identification of alunite can be aided with the sulfate zap test (Godwin, 2020).

TABLE 2. Generalized alteration facies and zones in epithermal deposits.
Location of precious-metal concentrations within these zones are italicized in the table and noted in the deposit models in Figures 24, 25 and 27. Additional codes are in TABLES A1 to A3. Mineral abundances in these zones are in TABLE 10. Abbreviations: ***HYP*** *= hypogene,* ***LCP*** *= lithocap,* ***AB*** *= albite,* ***AD*** *= adularia,* ***AL*** *= alunite,* ***BI*** *= biotite,* ***CA*** *= calcite,* ***CB*** *= carbonate,* ***CI*** *= cinnabar,* ***CL*** *= chlorite,* ***CP*** *= chalcopyrite,* ***EN*** *= enargite,* ***EP*** *= epidote,* ***GL*** *= galena,* ***IL*** *= illite,* ***KA*** *= kaolinite,* ***MM*** *= montmorillonite (smectite),* ***MS*** *= muscovite/sericite (white micas in general),* ***PP*** *= pyrophyllite,* ***QC*** *= quartz, chalcedony (agate),* ***QO*** *= quartz opal,* ***QW*** *= quartz angel wing.* ***QZ*** *= quartz,* ***SL*** *= sphalerite,* ***SS*** *= sulfosalts,* ***S**** *= native sulfur,* ***TR*** *= tremolite,* ***TT*** *= tetrahedrite-tennantite, and* ***ZE*** *= zeolite.*

ALTERATION NAME, ZONE OR FACIES & CODE	KEY DESCRIPTION	APPROXIMATE FORMATION TEMPERATURE (°C)
LITHOCAP LCP	**AT OR NEAR SURFACE**	
Steam heated STM = 9	**AL**, **CI**, **KA**, **QO**, **QZ**, **S*** Pervasive and open-space deposition	–
Sinter SIN = 8	**KA**, **QZ**, **QC** Rotten, porous, spongy and commonly bedded silica-carbonate zones. *Low-grade, bulk-mineable precious metals occur.*	–
Alunitic ALN = 7	**AL**, **QC**, **QZ**	–
Pyrophyllitic and/or kaolinitic PPT = 6	**KA**, **PP**, **QZ**	–
HYPOGENE HYP	**Approximate water table (fluctuates)**	
Bonanza base metal, BBM = 5	**AD**, **MS** (white micas), **QZ**, **QW**, **CP**, **GL**, **SL**, **SS, TT, EN** Sericitic, bonanza high-grade gold and silver and underlying base metal zones. Often throttle or boiling related. *Commonly rich in precious metals with local bonanza, high-grade lodes.*	**Less than** ~350°C
Illitic ILT = 4	**IL**, **QZ**, ± (**AD**, **BI**, **MM** [smectite]) *Low-grade precious metals occur.*	~250°C to ~350°C
Montmorillonitic (smectitic) MON = 3	**CL**, **CB**, **MM** (smectite), **ZE**	~150°C to ~220°C

Propylitic **PRP = 2**	**AB**, **CA**, **CB**, **CL**, **EP**, **ZE**	**Less than** ~150°C
Barren **BAR = 1**	Either, or both, late and early **QZ** and/or **CB** veins.	–
Fresh rock **FRX = 0**	Unaltered from regional background.	–

TABLE 3. Standard alteration facies or zones common to epithermal deposits.
Note that the abundant minerals, highlighted in red, trend generally from top left to bottom right. Location of precious-metal concentrations within these zones are noted and defined in this table and in the deposit models, below, in Figures 24, 25 and 27. Mineral abbreviations: ***AD*** *= adularia,* ***AL*** *= alunite,* ***BA*** *= barite,* ***CA*** *= calcite,* ***CB*** *= carbonate,* ***CI*** *= cinnabar,* ***CL*** *= chlorite,* ***EN*** *= enargite,* ***EP*** *= epidote,* ***G**** *= native gold,* ***GL*** *= galena,* ***HYP*** *= hypogene,* ***IL*** *= illite,* ***KA*** *= kaolinite,* ***LCP*** *= lithocap,* ***MK*** *= marcasite.* ***MM*** *= montmorillonite (smectite),* ***MS*** *= muscovite/sericite (including all white micas),* ***OP*** *= orpiment,* ***PO*** *= pyrrhotite,* ***PP*** *= pyrophyllite,* ***PY*** *= pyrite,* ***QC*** *= quartz chalcedony =* ***QG*** *= agate,* ***QO*** *= quartz opal,* ***QW*** *= quartz angel wing.* ***QZ*** *= quartz,* ***RG*** *= realgar,* ***S**** *= native sulfur,* ***SL*** *= sphalerite,* ***SS*** *= sulfosalts,* ***TE*** *= tellurides,* ***TT*** *= tetrahedrite-tennantite,* ***ZE*** *= zeolite. Abundance codes are* ***H*** *= high,* ***M*** *= medium,* ***L*** *= low,* ***T*** *= trace,* ***N*** *= nil, ± = plus or minus (i.e., optional).*

Mineralization -------------------- **Alteration facies and zone**	**S***	**QO**	**QC** **QG**	**QZ**	**AL**[#]	**PP**	**KA**	**MS** **IL**	**AD**	**PY** **MK** **PO**	**SS** **GL** **SL**	**MM**	**CA** **CB**	**CL** **EP**	**ZE**
Steam heated **STM = 9** **LCP**	**H** **±OP** **±RG**	**M** **±CI** **±S***	**L**	**H**	**H**	**M**	**N**	**N**	**N**	**T**	**N**	**N**	**N**	**N**	**N**
Sinter **SIN = 8** **LCP** ***Low-grade precious metals***	**N**	**N**	**H**	**H**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**±H**	**N**	**N**
Alunitic **ALN = 7** **LCP**	**N**	**N**	**H**	**H**	**H**	**M**	**M**	**T**	**N**	**N**	**N**	**N**	**N**	**N**	**N**
Pyrophyllitic **PPT = 6** **LCP/HYP**	**N**	**N**	**N**	**H**	**±H**	**H**	**M**	**L**	**N**	**N**	**N**	**N**	**N**	**N**	**N**
Sericitic and bonanza base metal **BBM = 5**	**N**	**N**	**N**	**H** **QW** **G*** **±TE**	**N**	**N**	**N**	**H**	**H**	**H**	**H** **±CP** **±TT** **±EN**	**N**	**±H**	**N**	**N**

HYP ***Low grade and bonanza grade in precious metals***															
Illitic **ILT = 4** **HYP** ***Low grade in precious metals***	**N**	**N**	**N**	**H G***	**N**	**M**	**N**	**H**	**M**	**M**	**N**	**H**	**N**	**N**	**N**
Montmoril-lonitic (smectitic) **MON = 3** **HYP**	**N**	**N**	**N**	**L**	**N**	**N**	**N**	**L**	**N**	**L**	**N**	**H**	**M**	**H**	**T**
Propyllitic **PRP =2** **HYP**	**N**	**N**	**N**	**L**	**N**	**N**	**N**	**N**	**N**	**L**	**N**	**L**	**H**	**M**	**L**
Barren **BAR = 1** **HYP (late or early)**	**N**	**N**	**N**	**H**	**N**	**N**	**T**	**N**	**N**	**±M**	**N**	**N**	**±M**	**M**	**M**
Unaltered **FRX = 0**	**N**	**N**	**N**	**T**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**T**	**T**

#*Alunite (**AL**): although commonly limonite stained, alunite can be white and extensive in the steam-heated zone, in contrast to occurrences in the hypogene zone where it is commonly pink, local in occurrence and vein related.*

Field identification of alteration facies depends primarily on the identification of mineral associations, as generalized in TABLES 2 and 3 (in Part 1), and in the models of facies distributions in Figures 24, 25 and 27. Definitive identification of some minerals requires application of thin section, XRD and/or spectral (e.g., SWIR) analyses. The following sections present hints on field recognition of the major facies.

a) 

b) 

Figure 18. Steam-heated lithocap facies (STM = 9) with native sulfur at a) Goldfields, central Nevada, United States and at b) McLaughlin, northwestern California, United States.

Native sulfur in these sinters was precipitated from steam generated above a water table. The Goldfields deposit is GF in Figure 34.

Steam-Heated Lithocap Facies (STM = 9)

Steam-heated lithocap facies (STM = 9) forms above the water table. Quartz (including opal) textures are commonly spongy and bedded. Native sulfur is diagnostic (Figures 18 and 19a); orpiment, realgar and cinnabar also occur (Figure 19a). Alunite, if unstained by limonite, is commonly white, powdery, and fine grained. Pyrophyllite, also white, can be extensive throughout this zone. Brecciation is common (Figure 19b).

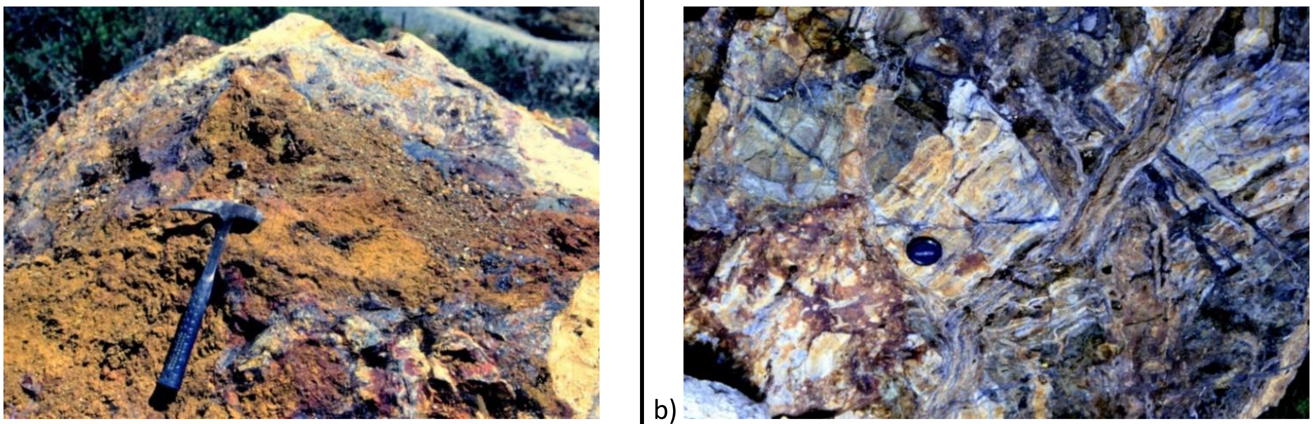


Figure 19. Steam-heated lithocap facies (STM = 9) at McLaughlin, northwestern California, United States.
***a)** Lithocap has limonite, native sulfur and red cinnabar, and **b)** brecciated and vein quartz.*

Sinter Lithocap Alteration Facies (SIN = 8)

Sinter lithocap facies (SIN = 8) is commonly formed at the surface from hydrothermal features such as hot springs and geysers (Hamilton et al., 2019). It commonly has laminated bedding from sequential deposition (Figures 20 and 21). Boiling mud pots can generate unique textures, such as geyser eggs (Figure 22). Clasts, bedded features and siliceous concretions or geyser eggs (formed in boiling pools) help to confirm an exhalative origin. Siliceous sinter represents higher temperature of formation than travertine carbonate; the former is considered more favourable for gold.

Figure 20: Sinter lithocap facies (SIN = 8) mound around a) geyser, b) mud pot, and c) terrace at Wairakei, New Zealand.
Laminated bedding, visible in c), is one important characteristic of the sinter lithocap facies.

Exhalative sediments associated with the sinter lithocap alteration are commonly geochemically enriched in Ag, As, Au, Bi, Fe, Hg, Li, P, Sb, W, Th, and Tl. Bladed carbonate-quartz angel wing habit, resulting from boiling, is an important precious metal index fossil. Angel wing habit is associated with the loss of CO_2 and S-species, which destabilizes gold when it is transported in sulfurous thio-complexes. If gold is present in the hydrothermal fluid, it cannot continue to be transported upon boiling upon release of sulfur and will be deposited.

Figure 21. Sinter lithocap facies (SIN = 8) from Gold Hill at Round Mountain Gold mine, Nevada, United States.
This feature has been mined out. Sinter lithocap can vary from thinly bedded to totally massive, recrystallized quartz. The Round Mountain mine is RM in Figure 34. Laminated bedding is common.

a) b) c)

Figure 22. Geyser eggs from a), b) Wairakei, New Zealand, and c) McLaughlin, California, United States.
Geyser eggs form at the surface in boiling mud pots.

Alunitic Lithocap Alteration Facies (ALN = 7)

Alunitic lithocap alteration facies (ALN = 7) is within the lithocap. Alunite in the lithocap, although commonly stained with limonite, can be white and it is commonly associated with kaolinite and quartz. Confirmation by XRD or spectral spectroscopy (e.g., SWIR) is usually necessary, but several zap tests are useful in the field (Godwin, 2020).

Pyrophyllitic Lithocap and/or Hypogene Alteration Facies (PPT = 6)

Pyrophyllitic lithocap and/or hypogene alteration facies (PPT = 6) spans the water table boundary between hypogene and lithocap alteration. When hypogene, alunite tends to be pink in tabular crystals. Occurrence in veins supports a hypogene origin. Because pyrophyllite is difficult to distinguish from muscovite or sericite in hand specimen and thin section, XRD or SWIR is usually necessary; once identified, the habit of pyrophyllite can be diagnostic. Pyrophyllite, as indicated in Figure 9a, forms at a higher temperature than kaolinite, muscovite or sericite. Green, chromium-rich muscovite mica (fuchsite or mariposite) is common where there is an original chromium content to the host rock. Hypogene pyrophyllitic alteration is commonly associated with breccia pipes and rhyolite domes.

Sericite–Base-Metal–Bonanza Hypogene Alteration Facies (BMB = 5)

Sericite–base-metal–bonanza hypogene alteration facies (BMB 5-ALT) occurs in the hypogene. It is a high-grade, bonanza zone, throttle or boiling related and often underlain by a base-metal–rich zone. Ore minerals are sphalerite, galena, chalcopyrite, sulfosalts (tetrahedrite, enargite), tellurides, and native gold or electrum.

Illitic Hypogene Alteration Facies (ILT = 4)

Illitic hypogene alteration facies (ILT = 4) is dominated by illite, but muscovite, sericite, adularia, and montmorillonite also occur. Illite (hydro muscovite) looks like sericite, but sometimes has a rainbow sheen in bright light. If the grains are fine, discrimination between the two minerals requires XRD or SWIR analysis. Coarse illite (hydro muscovite) looks like muscovite except the cleavage plates are not elastic.

Montmorillonitic (Smectite) Hypogene Alteration Facies (MON = 3)

Montmorillonitic (smectite) hypogene alteration facies (MON = 3) is part of the hypogene. Montmorillonite commonly occurs with some chlorite and carbonate. Montmorillonite (smectite) is drab olive-green and swells with added water. It can also be calcareous and fizz (as it swells) when tested with dilute (10%) hydrochloric acid.

Propylitic Hypogene Alteration Facies (PRP = 2)

Propylitic hypogene alteration facies (PRP = 2) is characteristically a drab green from chlorite and lesser amounts of epidote. Abundant pervasive or vein calcite, or other carbonate, makes the rock commonly effervesce when tested with dilute (10%) hydrochloric acid. Albite and pyrite are common. Note that blue green (sea green) celadonite commonly coats fractures and vesicles in volcanic rocks—even rhyolite—in the epithermal environment, and is commonly mistaken for chlorite, leading some to incorrectly assumptions of propylitic alteration.

Barren Hypogene Alteration Facies (BAR = 1)

Barren hypogene alteration facies (BAR = 1) is late and early barren veins, commonly quartz and/or carbonate.

Fresh Rock (FRX = 0)

Fresh rock (FRX = 0) is unaltered rock. This is not necessarily obvious because some altered rock can look fresh. A knowledge of regional rock types can be helpful, which emphasizes the need for regional geological mapping surrounding deposits.

Be sure you understand from this section the generalized:

- ➔ **lithocap alteration zones, and**
- ➔ **hypogene zones in epithermal deposits.**

IDEALIZED MODELS FOR EPITHERMAL DEPOSITS

In this section you will learn about the:

- ➔ **grade-tonnage model,**
- ➔ **generalized overview model of epithermal tops to porphyry bottoms,**
- ➔ **classic Buchanan epithermal model,**
- ➔ **classic high-sulfidation epithermal model,**
- ➔ **classic low-sulfidation epithermal model,**
- ➔ **overpressure thrust-detachment model, and**
- ➔ **Carlin model.**

Seven Models for Epithermal Deposits

Five models for epithermal deposits are the:

1. grade-tonnage model,
2. epithermal tops to porphyry bottoms model,
3. classic Buchanan model,
4. high-sulfidation model,
5. low-sulfidation model,
6. overpressure thrust-detachment model, and
7. Carlin-type gold model.

1. Grade-Tonnage Model

Grade-tonnage model of epithermal gold and silver deposits is in TABLE 4 (after Singer and Mosler, 1984). This table gives an overview of tonnage and metal potential in epithermal gold and silver deposits.

TABLE 4. Grade-tonnage model for epithermal gold and silver deposits
Table is after Singer and Mosler (1984).

Percentile	Tonnage (million tonnes)	Copper (%)	Lead (%)	Zinc (%)	Gold (g/t)	Silver (g/t)
Top 10	14.0	0.56	3.10	5.10	19.0	600
50	0.69	<0.04	<0.10	<0.10	4.3	130
90	0.066	–	–	–	0.1	18

2. Epithermal Tops to Porphyry Bottoms Model

A generalized overview model of epithermal tops to porphyry bottoms (Figure 23) is modified from White and Hedenquist (1995), and Hedenquist et al. (2000). This model shows the depth relationship between the epithermal deposit 'tops and porphyry deposit bottoms. Low-sulfidation epithermal deposits are dominated by a geothermal hot spring environment. High-sulfidation (or sulfateric) epithermal deposits have a dominantly volcano-magmatic signature; consequently, they generally form at higher temperatures. Intermediate-sulfidation epithermal deposits are recognized.

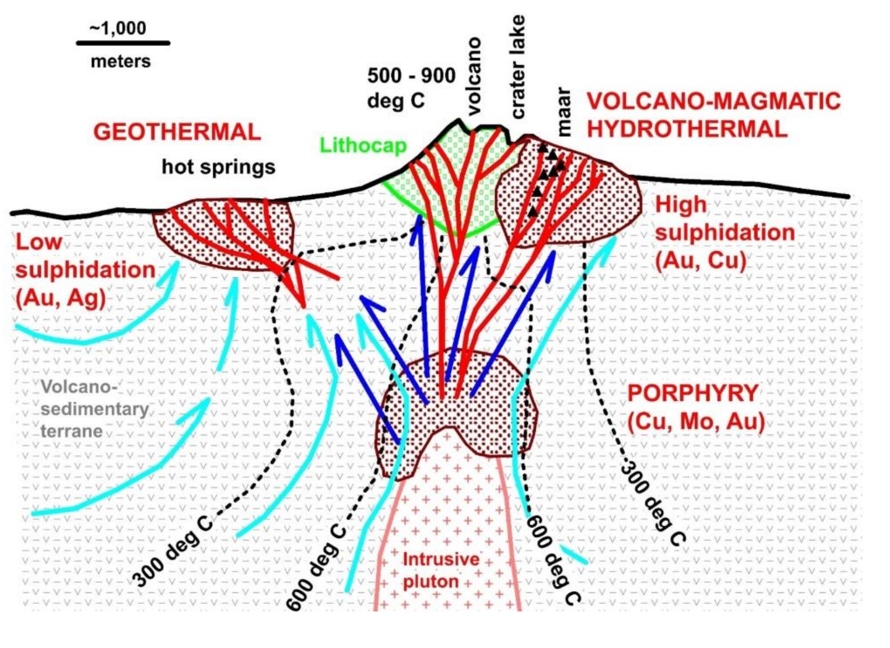


Figure 23. Generalized overview model for low- and high-sulfidation epithermal deposits.
Low-sulfidation epithermal deposits are dominated by a geothermal hot spring environment. High-sulfidation epithermal deposits have a volcano-magmatic signature and are closely associated with the lithocap. Pale blue arrows represent geothermal flow. Dark blue arrows represent magmatic-hydrothermal flux. Deposit localities are indicated by brown stippled shading. Model is modified from White and Hedenquist (1995), and Hedenquist et al. (2000).

Groundwater plays an important role because it can a) develop convection cells upon heating from igneous sources, b) scavenge ore metals from country rock through which it passes, c) mix with magmatic, ore metal components (Figure 23), and d) abruptly change the temperature of hot fluids by mixing (Figure 23), all of which can promote mineral precipitation. Groundwater is particularly important in low-sulfidation epithermal deposits but also can be involved in high-sulfidation epithermal deposits, as suggested by Berger (see insert *Interesting speculation on the role of topography and prevailing rain directions*). In lithocaps, the water table defines where downward percolating water causes supergene alteration to meet the horizontal plane at the top of hypogene alteration. Water tables, related to paleoclimatology and paleo-topography, fluctuate in level, which leads to complexities.

Interesting speculation on the role of topography and prevailing rain directions.

Most mineralization in the Goldfields gold camp in Nevada, United States (Figure 26 and GF in Figure 34), occurs on the western side of a volcanic complex. In a lecture years ago at The University of British Columbia, Byron Berger of USGS Menlo Park, California, United States, speculated that at the time of ore formation there would have been a volcanic edifice. Consequently, most of the rain would have fallen on the western side of the volcanic mountain because prevailing rains would have been from the west. This would favour hydrothermal circulation on the western side of the complex—coincident with the location of most of the deposits. Although speculative, this indicates why paleo-topography and paleoclimatology are likely to be significant exploration parameters.

3. Classic Buchanan Model

The Buchanan model (Figure 24, after Buchanan, 1981) was one of the first widely accepted epithermal deposit models, and it is still often referenced. The Buchanan model emphasizes occurrence of bonanza gold and silver grades at the throttle or boiling level (Figures 10 and 24). The lithocap is characterized by opaline silica and banded chalcedony in sinter terraces and a siliceous cap, which is underlain by alunite stockwork—all originally above the water table. At depth, pyrophyllite becomes more common because of magmatic temperature increase. Bonanza zone mineralization is characterized by banded, colloform, crustiform quartz, angel wing carbonate and/or quartz, adularia, native gold, native silver, electrum, and tellurides. Base-metal zone mineralization, below the throttle level, is characterized by massive quartz and the base-metal sulfides, which include arsenopyrite, sphalerite, galena, sulfosalts (e.g., tetrahedrite-tennantite, enargite) and chalcopyrite. The water table divides the upper lithocap from underlying hypogene mineralization, but its location changes and thus related features can be complex. The potential importance of breccia is indicated by its occurrence within the model.

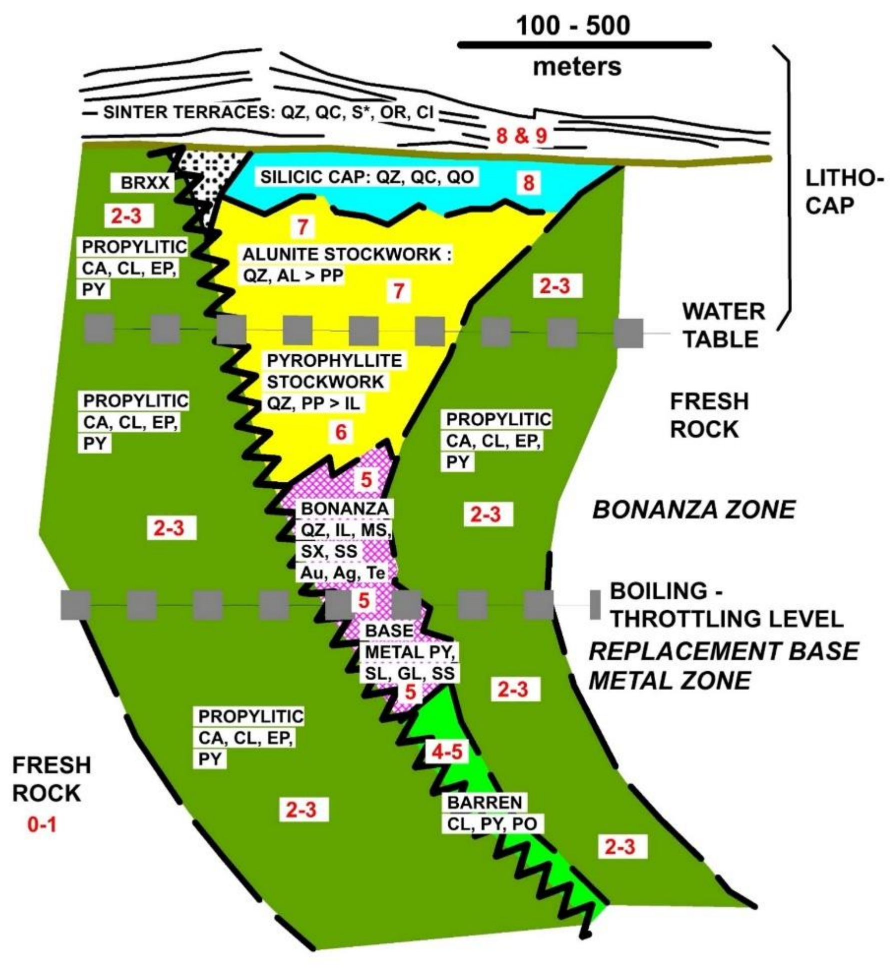


Figure 24. The Buchanan model for epithermal deposits.
The Buchanan model emphasizes occurrence of bonanza gold and silver grades at the throttle or boiling level. Abbreviations: ***AL*** *= alunite,* ***BRXX*** *= breccia (black speckled pattern),* ***CA*** *= calcite,* ***CI*** *= cinnabar,* ***CL*** *= chlorite,* ***EP*** *= epidote,* ***GL*** *= galena,* ***IL*** *= illite,* ***KA*** *= kaolinite,* ***MS*** *= muscovite/sericite,* ***OR*** *= orpiment (and realgar* ***RE****),* ***PO*** *= pyrrhotite,* ***PP*** *= pyrophyllite,* ***PY*** *= pyrite,* ***QC*** *= quartz chalcedony,* ***QO*** *= quartz opal,* ***QZ*** *= quartz,* ***SL*** *= sphalerite,* ***SS*** *= sulfosalts (e.g., tetrahedrite-tennantite and enargite),* ***SX*** *= sulfides, and* ***S**** *= native sulfur. Numbers* ***0*** *to* ***9*** *correspond to alteration facies summarized in TABLES 9 and 10. Model is after Buchanan (1981).*

4. High-Sulfidation Model

High-sulfidation epithermal deposits at Goldfields (GF in Figure 34), southwestern Nevada, United States, are illustrated in Figures 25 and 26. The district has been described by Berger and Bethke (1985) and Rockwell (2000). The high-sulfidation model in Figure 25 is after Arribas (1995) and Sillitoe (1999). Dome lamination and breccia has been added to the model based on the author's field experience with rhyolite domes. The model implies that it forms at the near surface top above a porphyry deposit bottom at depth; however, it is possible that the main features in the model of Figure 25 are related directly to rhyolite domes and that the vein(s) at depth could relate to the structure, which guided dome emplacement, rather than to an underlying porphyry deposit. In the absence of a rhyolite dome, especially if the lithocap has gusano texture in high-temperature pyrophyllite (Figure 16), a porphyry-type deposit at depth is possible.

The dominantly magmatic component results in a high sulfur content. One of the key manifestations of the sulfurous character is the extreme acid leaching that results in spongy quartz (Figure 17) and alunite. The rotten, spongy, and porous quartz is all that is left behind from extreme sulfuric acid leaching that even removes relatively stable aluminum; however, the spongy quartz can be rich in precious metals.

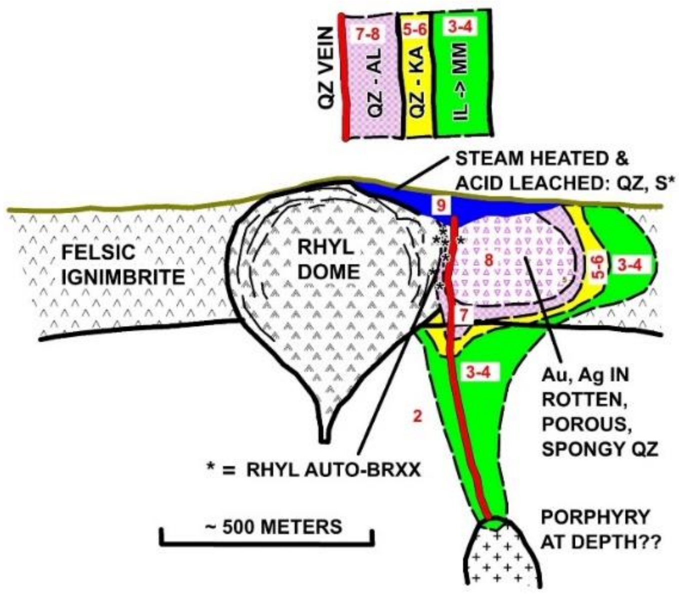


Figure 25. Classic high-sulfidation epithermal model. *The high-sulfidation model emphasizes higher grades of gold and silver in rotten, porous, spongy quartz residual from extreme acid leaching. Dome lamination and auto-breccia has been added based on the author's field experience with rhyolite domes. Abbreviations:* ***AL*** *= alunite,* ***BRXX*** *= breccia (Auto-**BRXX** = auto-breccia),* ***IL*** *= illite,* ***KA*** *= kaolinite,* ***MM*** *= montmorillonite (smectite),* ***QZ*** *= quartz,* ***RHYL*** *= rhyolite and* ***S**** *= native sulfur. Numbers* ***2*** *to* ***8*** *correspond to alteration facies summarized in TABLES 2 and 3. Model is after Arribas (1995), and Sillitoe (1999).*

a)

b)

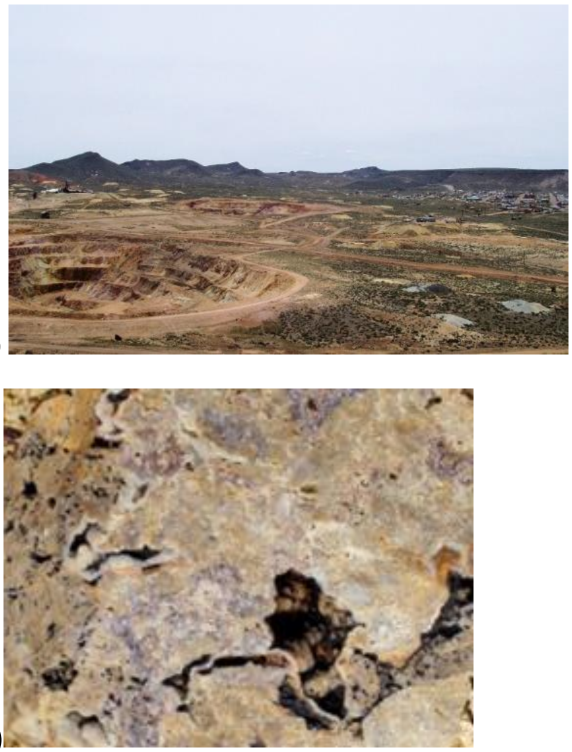


Figure 26. Features of the high-sulfidation epithermal deposits at Goldfields, southwestern Nevada, United States.
a) *Overview of the town of Goldfield, Nevada, with old workings in the background on the west side of the original volcanic complex.* ***b)*** *Spongy quartz indicates extreme acid leaching (facies* ***SIN*** *=* ***8*** *of TABLES 2 and 3) that is characteristic of high-sulfidation epithermal deposits (Figure 25). The Goldfields deposit is GF in Figure 34.*

Porphyry intrusion that is inferred at depth (or as implied in this Figure 25 cartoon model, in the rhyolite dome alone) provides the magmatic hydrothermal fluids and high temperature necessary to generate pyrophyllite. Consequently, in Figure 25, the main vein fracture (red) may have been a guide to intrusion of the rhyolite dome rather than a link to an underlying porphyry deposit.

Rhyolite domes have margins that are often flow banded—a feature that sometimes enables determination of upward and lateral movement. The core is commonly massive, but changes upward and outward, first becoming increasingly flow-banded due to viscous rhyolite expansion on intrusion, then finally becoming auto-breccia (fragments of dome rhyolite only in a rhyolitic matrix) due to the explosive release of magmatic fluids. The breccia can be mineralized and hot enough for pyrophyllite alteration adjacent to the dome (alunitic [**ALN** = **7**] and pyrophyllitic [**PPT** = **6**] alteration). The direction of movement the flank of a dome can point toward a lateral, high-sulfidation epithermal deposit.

5. Low-Sulfidation Model

The low-sulfidation model (Figure 27) is after Hedenquist et al. (2000). The model emphasizes the important role of appropriately permeable horizons that become mineralized. The centre of the ore zone corresponds closely to that in the Buchanan model (Figure 24).

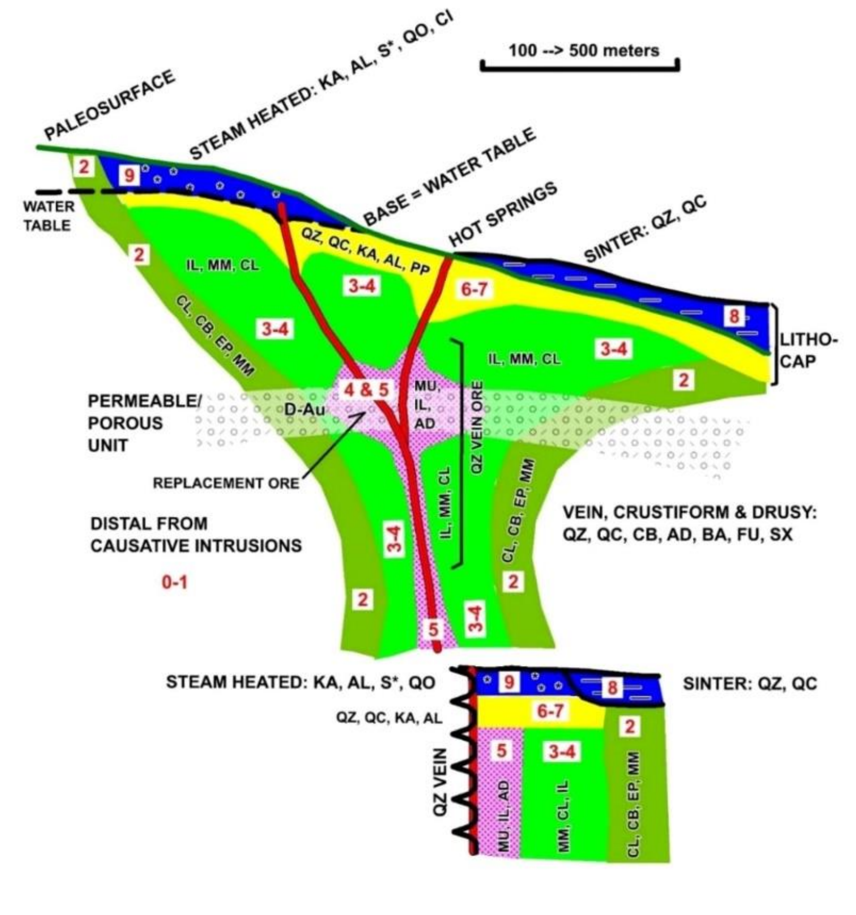


Figure 27. Classic low-sulfidation epithermal model.
Low-sulfidation model emphasizes trapping of higher grades of gold and silver in favourable, porous stratigraphic units. Abbreviations: ***AD*** *= adularia,* ***AL*** *= alunite,* ***BA*** *= barite,* ***CA*** *= calcite,* ***CB*** *= carbonate,* ***CI*** *= cinnabar,* ***CL*** *= chlorite,* ***EP*** *= epidote,* ***FU*** *= fuchsite (mariposite),* ***IL*** *= illite,* ***MM*** *= montmorillonite (smectite),* ***MU*** *= muscovite/sericite (white micas),* ***PP*** *= pyrophyllite,* ***QC*** *= quartz chalcedony (agate* ***QG****),* ***QO*** *= quartz opal,* ***QZ*** *= quartz,* ***SX*** *= sulfides and* ***S**** *= native sulfur. Numbers* ***0*** *to* ***9*** *correspond to alteration facies summarized in TABLES 9 and 10. Model is after Hedenquist et al. (2000).*

Round Mountain mine (Figures 28, and RM in Figure 34; Berger and Bethke, 1985) in central Nevada, United States, is a classic example of a low-sulfidation gold deposit, as are the famous low-sulfidation epithermal gold deposits in the Comstock District, near Reno, northwestern Nevada, United States (Hudson, 2009).

Figure 28. Low-sulfidation epithermal deposit, Round Mountain, central Nevada, United States.
The people at the bottom of the pit in b) give an indication of the huge size of this deposit, pictured in a). Originally there was a sinter cap at the top of the deposit (Figure 21). The Round Mountain deposit is RM in Figure 34.

6. Overpressure Thrust-Detachment Model

The overpressure thrust-detachment model seems to be related to the soda can- thrust faulting model popularized by M. King Hubbert (Hubbert and Rubey, 1959). The soda can-thrust model is based on the movement of an empty, cold, pop can placed upside down on a gently inclined sheet of glass. As the soda can warms, moisture condensation from the outside of the can seals the contact between the can and the glass, the air expands inside the can and the buoyed can slides down the gently inclined glass because the water interface has no shear strength. The translation to thrust detachment faults (Figure 29) is that hydrothermal pressure build-up (overpressure raises the upper plate) in the low-angle fault plane allows massive movement of the upper plate because of the reduction in normal force friction and the lack of shear strength in the fluid. The hydrothermal fluid in the thrust can also be responsible for mineralization.

Potential sites for epithermal mineralization related to hydrothermal fluids responsible for thrust detachment in shallow continental environments are shown in Figure 29, which is modified from Wilkins et al. (1986). Epithermal deposits can form (with reference to Figure 29):

- on the plane of the thrust detachment fault (**1**),
- in listric faults zones splaying from the thrust detachment fault (**2**),
- as veins in fold structures related to the structural forces of the thrust detachment fault (**3** and **4**), and
- by replacement in amenable beds above or below the plane of the thrust detachment fault (**4** and **5**).

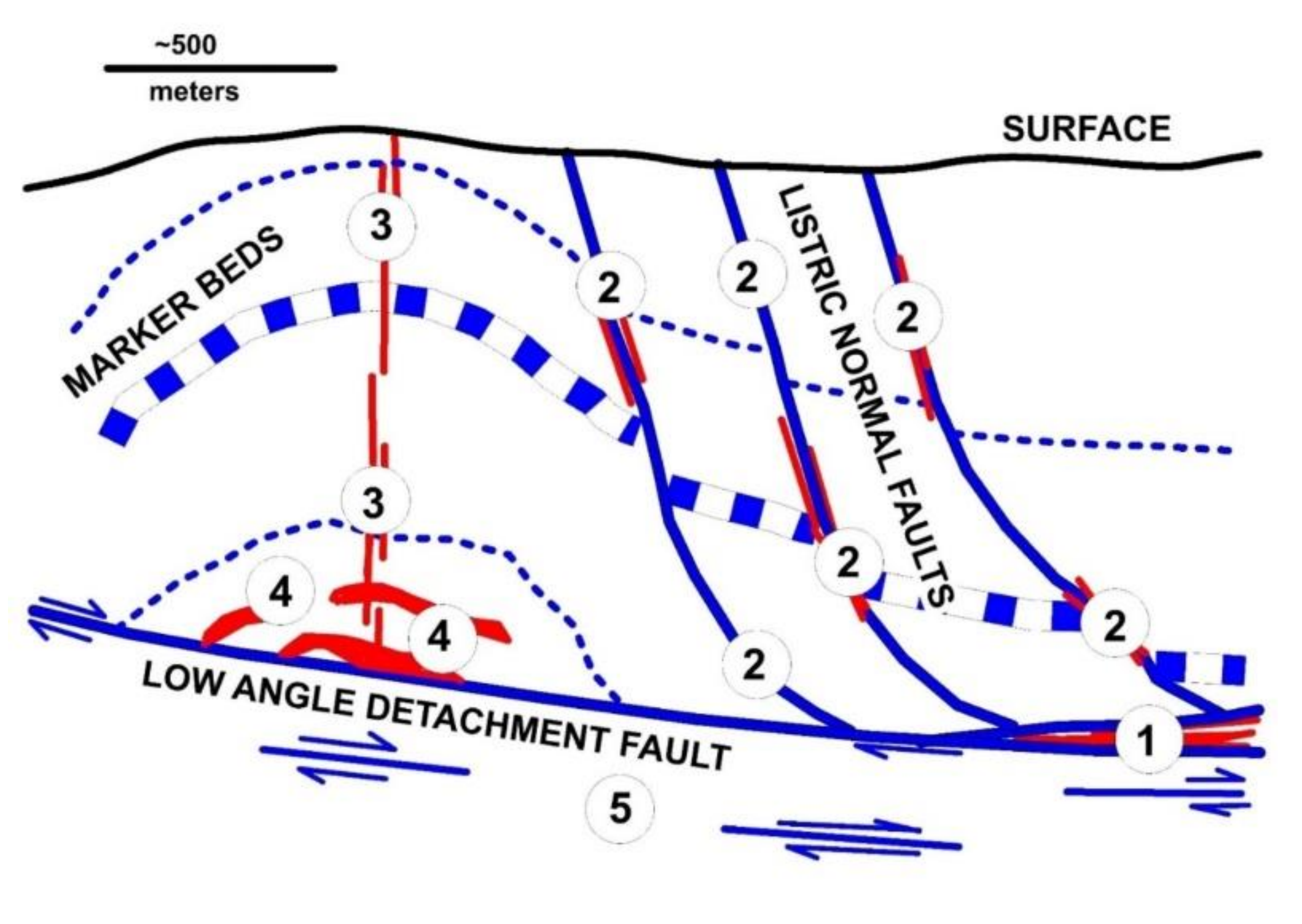


Figure 29. Overpressure thrust detachment model.
Mineralization results when hot brines are expelled from a synorogenic basin or from intrusive rocks during thrust detachment in a shallow epithermal environment. Faults are drawn as thick blue lines. Mineralization (red lines and zones) can occur in all numbered locations: 1 = on the plane of the thrust detachment fault, 2 = in listric normal faults and associated breccias, 3 = as replacement in fold axis veins (and in extension fractures at right angles to these), 4 = as replacement in permeable, porous, and reactive units, and 5 = extending into the footwall of the thrust detachment fault. Model is modified from Wilkins et al. (1986).

Reactive or altered host rock, structural dilation and associated brecciation favour ore mineralization. Hot brines (potentially with gold chloride or sulfurous gold thio-complexes) in thrust detachment faults can be expelled from the synorogenic basement, or perhaps from spatially related intrusions.

Regional mapping around the ore deposit is necessary to establish the possibility that a detachment thrust fault might be important. La Jojoba in northern Sonora, Mexico, and Bullfrog in southwestern Nevada, United States (BF in Figure 34) are possible overpressure, thrust detachment fault–related epithermal gold deposits.

The La Jojoba epithermal gold mine in northern Sonora, Mexico, has gold mineralization in low-grade metamorphic rocks in an upper plate, which has been thrust over the higher-grade metamorphic rocks of the lower plate. The thrust detachment surface does not have significant gold mineralization, but it is marked by altered gouge and breccia zones up to about 10 metres in thickness. It is not entirely clear that the mineralization is epithermal. Although there are some vuggy textures, there also is potassic alteration more akin to porphyry-style gold mineralization. The metamorphic host is, of course, not common for epithermal deposits.

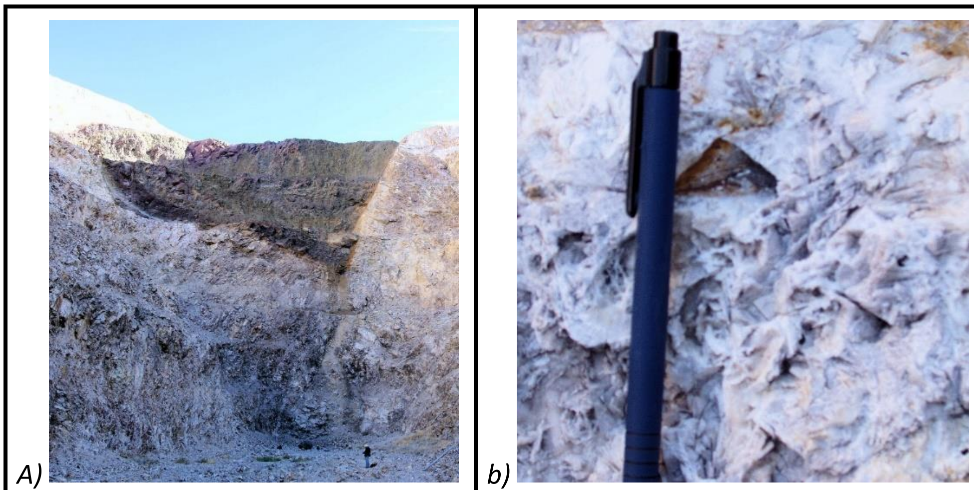


Figure 30. a) Steep normal vein fault with b) angel wing quartz at the Bullfrog gold mine, southwestern Nevada.
***a)** A normal fault at the end of the open pit likely taps auriferous brines from an underlying thrust or detachment fault, which is mapped below the open pits in this area. **b)** Angel wing habit is abundant throughout the mine area and indicates that vein fault boiling is an important cause of gold deposition. The pictures are from the Bullfrog gold mine, southwestern Nevada, United States (BF in Figure 34).*

The Bullfrog epithermal gold mine, shown in Figure 30, is in southwestern Nevada, United States (BF in Figure 34). Regionally, as shown by mapping, the mine area is underlain by a thrust detachment fault (point **5** in Figure 29). However, the mined veins are steep (Figure 30a), apparently corresponding to the listric normal faults (point **2** in Figure 29). The angel wing habit (Figure 30b) is diagnostic of boiling; consequently, the gold mineralization occurs because of boiling in a listric normal fault that is apparently related to an underlying thrust detachment fault.

7. Carlin-Type Gold Model

Carlin-type gold deposits in northern Nevada contain more than 5,500 tonnes of gold, the second largest concentration of gold in the world after what most consider to be paleo-placer gold deposits in South Africa. Gold occurs as finely disseminated, micron gold in decalcified and silicified carbonaceous-silty limestone. Characteristically, values of gold are higher than those of silver, arsenic, antimony, mercury, and thallium; values of lead and zinc are generally low. Gold as solid solution/replacement in pyrite or as sub-micrometre particles results in refractory ore—unless oxidized by supergene processes (oxidation facilitates heap leaching). Host rocks are mainly carbonaceous, lower Paleozoic miogeoclinal carbonate rocks. Deep-tapping, abyssal, high-angle normal faults are important fluid pathways and guides to hydrothermal fluids from which ore mineralization was precipitated. The presence of impermeable rocks in overlying thrust plates, such as those above the Roberts Mountain thrust (Figure 34), might promote lateral dispersion of mineralized fluids into reactive host rocks in the underlying plate. Intense decalcification from acid hydrothermal dissolution of carbonate rock leads to the development of collapse breccias, which can simultaneously or subsequently become mineralized. Silicification and jasperoid in central parts of the deposit can be associated with quartz, illite, kaolinite and montmorillonite (smectite; Kuehn and Rose, 1992). Carlin-type deposits are not restricted to Nevada, United States, but occur in various locations around the world. They are well documented in locations such as China (Jinfeng in southwestern China; Chen et al., 2011); Yukon, Canada (Atac Gold's Carlin-type deposits on the northeastern margin of the Selwyn Basin in central-eastern Yukon; Arehart et al. [2013]) and Iran (Zarshuran in northwest Iran; Paravarzar et al. [2015]).

There is no universally accepted genetic model. Suggested models make connections to magmatism, regional metamorphism or regional extension. Although many have described Carlin-type deposits as epithermal (e.g., Radtke, 1985), this is debatable; however, they are included as epithermal here because most are young (Eocene to Oligocene—42 to 34 Ma [Muntean et al., 2011]), drusy quartz veins are common and intrusive rocks (e.g., dike in Figure 33) were intruded near the surface (1 to 3 kilometres). They are not hosted in volcanic rocks, as is characteristic of most epithermal deposits discussed in this guide. Instead, they form in carbonaceous to carbonate rocks that formed along hinge lines where basinal facies interfinger with platformal carbonate rocks (Figure 34).

The origin of gold is magmatic, as argued convincingly by Muntean et al. (2011). Specifically, the author's speculative interpretation is that the trendlines of the gold deposits (e.g., the Carlin trend and the Battle Mountain trend; Figure 34) mark abyssal faults and underlying intrusive gold source trends that intersect the carbonaceous traps formed at the Nevada hinge line. Thus, the Carlin-type gold deposits occur at the intersection of a) the mainly underlying northwest-trending intrusions and structures that source hydrothermal gold, with b) the north-south–trending pyritic carbonaceous hinge line trap rocks that promote gold replacement and gold precipitation by coupled oxidation-reduction of carbon and gold in hydrothermal solutions (EQUATIONS 1 to 4). It must be taken into consideration that Hofstra and Cline (2000) state that carbon played little or no role in gold precipitation in the Carlin-type deposits in Nevada, United States, although the carbonaceous material could have been a source of sulfur used to transport gold in hydrothermal fluids to sites of ore deposition. In contrast, however, Gu et al. (2012) note that the Youjiang basin in southern China contains many Carlin-type gold deposits and abundant paleo-oil reservoirs. They state that 'The close association of Carlin-type gold deposits and paleo-oil reservoirs, the paragenetic coexistence of bitumen with ore-stage minerals, the presence of abundant hydrocarbons in the ore fluids, and the temporal coincidence of gold mineralization and hydrocarbon accumulation all support a coeval model in which the gold originated, migrated, and precipitated along with the hydrocarbons in an immiscible, gold- and hydrocarbon-bearing, basinal fluid system'. Hulen et al. (1998) note that 'The Carlin-type disseminated gold orebodies of Yankee basin in the southern part of the Alligator Ridge [AR in Figure 34] mining district in Nevada, United States, contain widespread oil as smears, open-space fillings, and fluid inclusions in syn- and pre-mineral calcite veins.' Furthermore, fractal modeling of the Zarshuran Carlin-type gold deposit in northwest Iran indicates that gold mineralization correlates positively with black rock (93.48%), jasperoid (92.5%), carbonaceous rock (52.90%), fault gouge and breccia (Paravarzar et al., 2015). Additionally, Large et al. (2011) suggest that carbonaceous sedimentary rocks in reduced continental margin settings are a feasible source for gold and arsenic in Carlin-type deposits.

The Carlin-type model proposed here emphasizes the intersection of an intrusive/structural gold source and a carbon trap in carbonaceous, phosphatic rocks associated with a hinge line (Figure 34). The hydrothermal fluids emanate from long linear intrusive trends that also follow deep, abyssal structural zones. Thus, the linear Carlin and Battle Mountain trends in Figure 34 reflect the intersection of linear intrusive and associated deep structural trends, which commonly show up as volumetrically minor intrusions (such as the minor dike in Figure 33) that source introduced hydrothermally transported gold. Most gold in Nevada occurs along the hinge line between a westerly basin and an eastern platform. The hinge line is marked by a) locally petroliferous, basinal, black carbonaceous shale interfingered with continental-shelf carbonaceous carbonates (Figure 34), b) SEDEX barite and sulfide deposits, c) phosphatic variscite (see insert *Hinge line marker by the green phosphate mineral variscite*) and turquoise, and locally d) uraniferous-phosphatic minerals such as yellow autunite and green torbernite. Thus, the hinge line becomes the carbon trap in which the carbon is available for coupled oxidation-reduction of gold sourced as hydrothermal fluids from underlying and minor intrusive rocks along major structures (see insert *Associations among carbon trash, uranium and gold at Bald Mountain Wash, central Nevada, United States*). Gold and arsenic can also replace pyrite, which is commonly abundant in carbonaceous carbonate rocks. At this intersection of source and trap, the resulting geochemical associations with Carlin-type deposits are likely to be:

- intrusive/hydrothermal–related gold greater than silver, arsenic, mercury, tellurium, and thallium,
- black shale and hinge line–related phosphorous, vanadium, uranium and petroleum, and
- basinal brine and SEDEX deposit–related silver, barite, lead, zinc, and cadmium.

Hinge-line marker by the green phosphate mineral variscite.

The potential importance of hinge lines as a carbon trap that facilitates the formation of gold was brought to my attention during two Nevada field trips (sponsored by the Great Basin and Western Cordilleran Society) in 2003 and 2005 that visited major Carlin-type deposits. The most obvious evidence of carbon enrichment, shown in Figures 31 and 32, is the black carbonaceous character of the carbonates exposed in the open pits. A second observation was that most examples of gold-rich core that were set out contained the green, waxy-looking, phosphate mineral variscite. Variscite is a semiprecious mineral that is commonly in the Phosphoria Formation of the western United States. The Phosphoria Formation formed at an early Permian hinge line, where upwelling from an oceanic basin was a result of hot, continental shelf environments; such upwellings are marked by intense biological activity. This anomalous organic activity at a hinge line is akin to that off the arid, southwestern coasts of Africa and South America today. In these areas (as in similar environments in the past) prolific biogenic activity is marked by fish and other sea life populations feeding in upwelling cold, oxygen- and nutrient-rich Antarctic water. Resulting rocks formed in these zones do not have a high clastic component because of the arid, offshore climate but characteristically have a high concentration of skeletal phosphate, as well as carbon-rich petroleum, uranium and vanadium. Thus, the presence of variscite in the Nevada, United States, gold deposits is a good indication that the rocks containing it also will have a high-carbon oil trap component that is spatially related to a hinge line.

Figure 31. Northumberland mine, a Carlin-type deposit in central Nevada, United States.
Photos of the Northumberland pit (NU in Figure 34) taken in 2005. The black colour of the host rock is noteworthy and clearly indicates that it is carbon rich. Note the supergene limonite after disseminated sulfides, mainly pyrite.

Figure 32. An open pit wall at the Mother Lode Carlin-type deposit in southern Nevada, United States.
The photos of the inactive Mother Lode pit (ML in Figure 34) taken in 2003. The dark carbonaceous component of the carbonate is apparent in both the a) general and b) more detailed views.

Hinge lines mark crustal, deep, abyssal structures that might also be associated with intrusions with unique properties, such as association with gold and silver (e.g., Round Mountain gold mine [RM in Figure 34] and Tonopah silver mine in central Nevada, United States [photograph on back cover]). They also are well known for associated SEDEX deposits (lead, zinc, barite ±silver), especially in structurally related second- or third-order basins (in Nevada, United States, some deposits in the Carlin trend have SEDEX characteristics that have been overprinted with gold; the SEDEX-bedded barite belt is well known).

Justification for the Carlin-type gold deposit model, as proposed, is supported by the following major features in Nevada, United States, as shown in Figure 34:

- The north-south band that marks the Nevada hinge line (diagonal black lines; after Stewart [1980]) hosts most of the gold in Nevada.

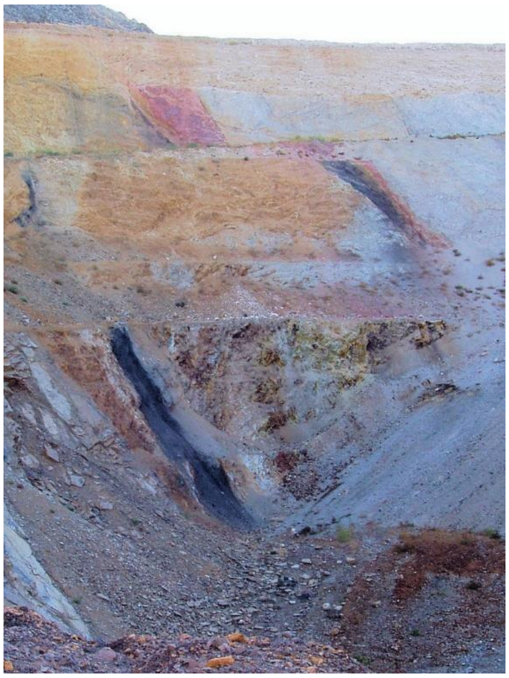


Figure 33. Single mafic dike in the open pit of the Mother Lode Carlin-type deposit in southern Nevada, United States. *The dike is the brown outcrop near the centre of the top bench; it also cuts the bench face in the level below it. Gold grades in reconnaissance samples near the dike were higher than those taken randomly in the pit. The Mother Lode deposit is ML in Figure 34.*

- The Nevada hinge line formed east of the continental margin, as indicated by $(Sr/Sr)_i$ = 0.705 (Scott et al., 1971), and marks the transition of rocks from carbonaceous, basinal facies to platformal carbonates; upwelling along the hinge line is driven by winds from the west (platformal carbonates indicate a hot continental climate, assuring onshore winds) is organic productive and leads to enrichment in biogenic carbon-rich petroleum, phosphate (variscite, turquoise), vanadium and uranium concentrations (cf. Phosphoria Formation [Gulbrandsen, 1966]).
- The Nevada hinge line represents a major structural, abyssal, crustal break that divides basinal (deep) shale-rich facies to the west from carbonate-rich platformal facies to the east.
- The locus of the Nevada hinge line moved back and forth, from east to west, from Ordovician to Permian (Stewart, 1980), and the resulting carbonaceous phosphatic upwelling-related rocks formed a band up to about 100 km wide east to west.
- The Roberts Mountain Formation, a common host rock to Carlin-type gold mineralization at the Nevada hinge line, is carbonaceous carbonate.
- The Nevada hinge line is also marked by SEDEX deposits, particularly Nevada barite-phosphate lodes, that form a north-south band of occurrences (area outlined in purple after Coles [1996]); this barite band is confirmed, and somewhat expanded, based on analysis of government silt geochemical barium data (purple stippled pattern; NURE: National Uranium Resource Evaluation regional geochemical survey by the United States Geological Survey; USGS).
- Famous gold trends, like Carlin and Battle Mountain (black dashed lines), probably represent abyssal, structural trends and underlying plutons—perhaps including gold porphyry systems at depth—that facilitate intrusion of small high-level intrusive rocks such as dikes; hydrothermal solutions from the intrusive rocks provide the gold, which is precipitated by a) reduction of gold coupled with oxidation of carbon in the hinge line trap (see equations 3 to 6, and the insert *Associations among carbon trash, uranium and gold at Bald Mountain Wash, central Nevada*), and b) replacement of authigenic pyrite.
- Because most Carlin-type deposits are in the footwall to the Roberts Mountain thrust—the eastern limit of which is shown (green thrust line)—there is a possibility that the thrust functioned as an aquiclude that forced the underlying hydrothermal system to spread laterally to form larger deposits.
- Most of the United States government's silt samples (USGS) that have a Carlin-type signature (red stars in Figure 34; based on discriminant factors using RDVM analysis; Godwin, 2016) are in the band marking the Nevada hinge line.

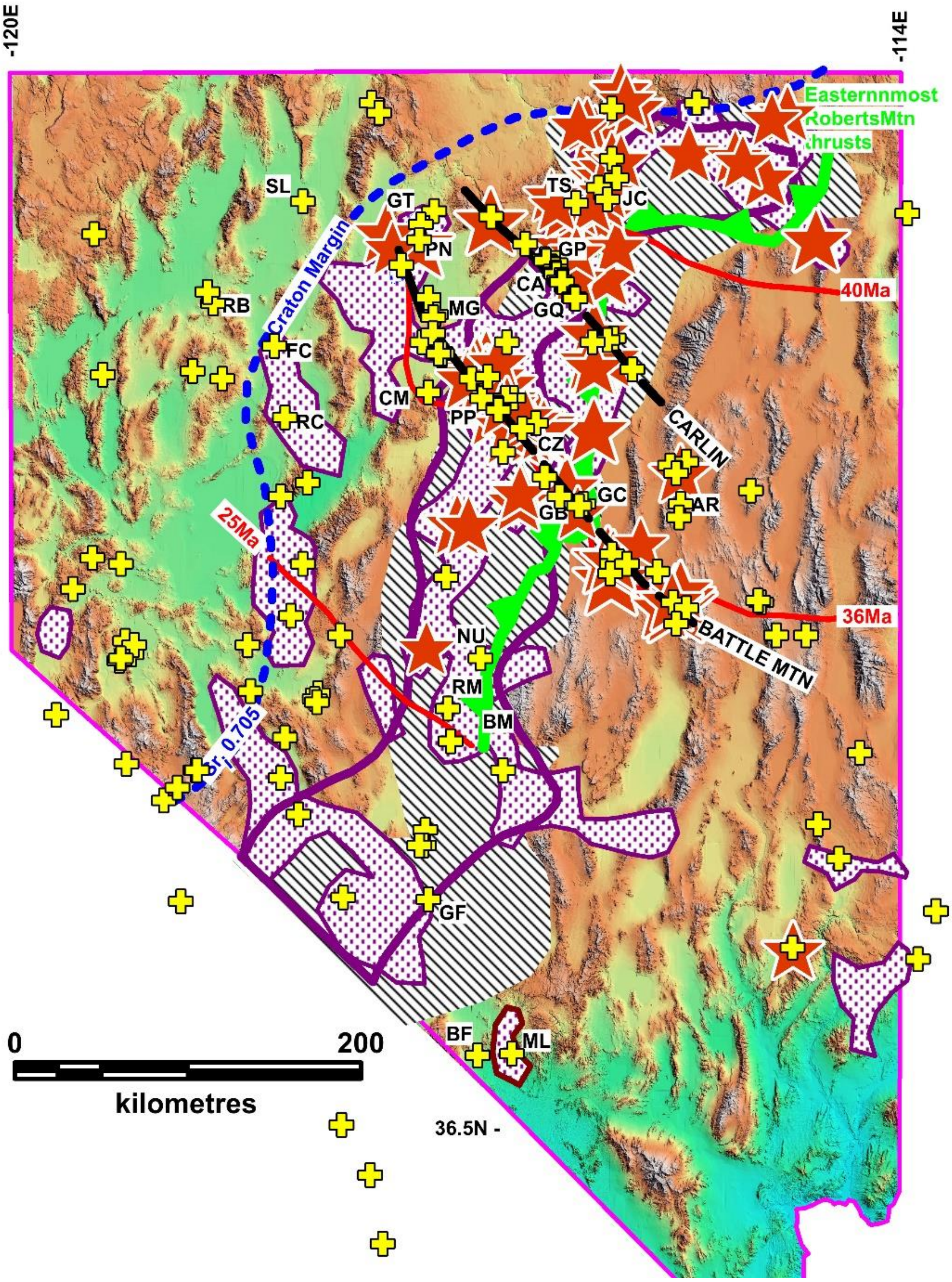


Figure 34. Association of Carlin-type gold deposits in Nevada, United States, with the hinge line and barite belt. *Dashed black lines mark the Battle Mountain (BATTLE MTN) and the Carlin (CARLIN) trends of Carlin-type deposits. Yellow crosses = major deposits from MRDS (USGS) database. Labelled gold deposits are AR =*

Figure 34 continued: Alligator Ridge, BF = Bullfrog, BM = Bald Mountain Wash, CA = Carlin, CM = Cove–McCoy, CZ = Cortez, FC = Florida Canyon, GB = Gold Bar, GC = Gold Canyon, GF = Goldfields, GP = Goldstrike–Post, GQ = Gold Quarry, GT = Getchell, JC = Jerritt Canyon, MG = Marigold, ML = Mother Lode, NU = Northumberland, PN = Pinson, PP = Pipeline, RB = Rosebud, RC = Relief Canyon, RM = Round Mountain, SL = Sleeper and TS = Tuscarora. Red lines = Carlin-causative intrusive age contours (25, 36 and 40 Ma from Muntean et al. [2011]). Diagonal black lines = band representing the Nevada hinge line locations from the Ordovician to the Permian (Stewart, 1980). Purple outline = sedimentary exhalative barite with phosphate occurrences (Coles, 1996). Blue dashed line = Craton margin, initial strontium ratio 0.705 (Scott et al., 1971). Green thrust line = easternmost extent of Roberts Mountain thrust. Stippled purple areas = anomalous barium based on NURE (National Uranium Resource Evaluation) regional geochemical survey by the United States Geological Survey; USGS) silt geochemistry and red stars = silt samples with a Carlin-type signature (RDVM analysis [Godwin, 2016] of NURE silt samples). Background is colour-contoured digital elevation.

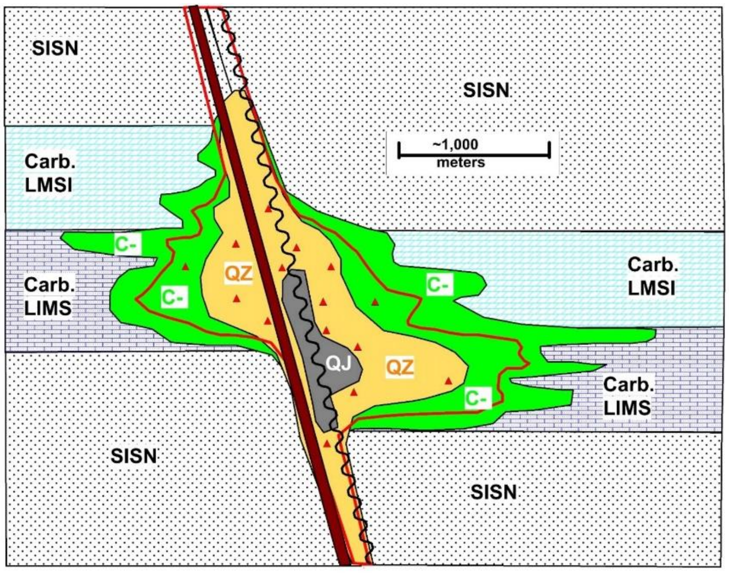


Figure 35. Model for Carlin-type gold deposits.
C- *= decalcification of carbonate rock with volume shrinkage commonly resulting in potentially mineralized collapse-dissolution breccias (red triangles), which can be well mineralized.* ***QJ*** *and* ***QZ*** *= jasperoid quartz and silicified quartz with associated illite, kaolinite and montmorillonite (smectite);* ***Carb. LIMS*** *= carbonaceous limestone;* ***Carb. LMSI*** *= carbonaceous silty limestone; and* ***SISN =*** *siltstone.* ***Wavy black line*** *= high-angle, abyssal fault zone with access to underlying plutons, including, perhaps, gold porphyry systems.* ***Brown band*** *= Eocene–Oligocene intrusive rocks, commonly of minor volume within the Carlin-type deposits.* ***Red outline****: = Carlin-type micron gold mineralization with associated auriferous pyrite and associated arsenic, antimony, and mercury minerals, but a general absence of lead and zinc minerals. Figure is modified from Robert et al. (2007) by the addition of a dike and the carbonaceous components to some of the carbonate rocks.*

The generalized model for Carlin-type deposits, presented in Figure 35, is modified from Robert et al. (2007). Key features of the model are:

- *Host rocks*: carbonaceous limestone (labelled **Carb. LIMS**) and carbonaceous, silty limestone (labelled **Carb. LMSI**) are common hosts to Carlin-type gold ore. Siltstone (labelled **SLSN**), without a carbonaceous component, is generally not well mineralized.
- *Structure*: deep, abyssal, normal fault structures (black, wavy line) provide the hydrothermal gold source access to the carbonaceous carbonate trap; the intersection of these normal faults with the base of thrust fault aquicludes might be particularly important.
- *Intrusive rocks*: intrusive rocks are rare and sometimes only represented by dikes of minor dimensions (brown in Figures 33 and 35). These dikes, and assumed plutons at depth, are the source of the gold-bearing hydrothermal solutions that are structurally guided along faults to the carbonaceous-carbonate trap.
- *General alteration*: intense decalcification (green areas labelled **C-**) from acid hydrothermal dissolution of carbonate rock leads to development-sanded carbonate rock and collapse breccias (red triangles). The collapse breccias can become mineralized during or after formation.
- *Central alteration*: quartz silicification in central parts of the deposit can be associated with vuggy quartz, illite, kaolinite and montmorillonite (smectite; Kuehn and Rose [1992]).
- *Core alteration*: jasperoid, formed by silica replacement of carbonate, resembles jasperoid or chert formed by sedimentary processes (distinction is discussed in the insert *Hints for distinguishing jasperoid from chert*).

- *Mineralization*: commonly associated minerals within the ore zone (the area enclosed by the red line) are arsenopyrite, barite, calcite, carbon-graphite-petroleum, cinnabar, goethite, gold greater than silver (native and in solid solution: micrometre or invisible), illite, jarosite, kaolinite, limonite, montmorillonite (smectite), orpiment, pyrite (arsenian), crystalline quartz, jasperoid quartz, realgar and variscite. Base-metal minerals like galena and sphalerite are rare.

Hints for distinguishing jasperoid from chert.

Jasperoid is a dense, white to grey, chert-like siliceous rock in which chalcedony or cryptocrystalline quartz has replaced carbonate. It is classically associated with Carlin-type gold deposits. The trick is distinguishing jasperoid alteration from primary, sedimentary chert. Lovering and Hamilton (1962) note several distinguishing criteria: compared to chert, jasperoid commonly has a) vuggy texture visible in hand specimen, b) phaneritic crystallinity (in thin sections of quartz the largest grain diameter is more than 10 times the smallest grain diameter), c) abundant goethite, jarosite and pyrite (or pseudomorphs), and d) anomalous amounts of As, Sb, Hg, Ba, Tl, Bi and Fe (>1.5%) and locally, Au and Ag. Thus, whole-rock geochemical analysis of suspected jasperoid is warranted. Nelson (1990) analyzed a database of 272 samples of jasperoid by factor analysis, which indicated that it is anomalous in Li, P, Mn, Ba, Mo, Cr, Co, V, Cd, Ni, U, Zn and Pb. Significantly, metalliferous marine black shales are enriched in these elements and are spatially related to Carlin-type gold deposits.

Be sure you know from this section:

- ➔ **the seven basic models for epithermal deposits,**
- ➔ **how epithermal deposits rank by tonnage and grade,**
- ➔ **the generalized epithermal top and porphyry bottom model,**
- ➔ **what a high sulfidation model is,**
- ➔ **what a low sulfidation model is,**
- ➔ **what an overpressure, thrust-detachment model is, and**
- ➔ **why Carlin-type deposits might result from an intersection of a magmatic source and a carbonaceous trap.**

SUMMARY AND CONCLUSIONS FOR EPITHERMAL DEPOSITS

In this section you will find:

- ➔ **a tabulation of general characteristics of epithermal deposits, and**
- ➔ **a summary of typical epithermal alteration facies.**

Summary of General Characteristics for Epithermal Deposits

Descriptions of epithermal deposits in Part 2 of this guide have emphasized common-sense principles applicable to field exploration without recourse to fluid inclusion microscopes, isotopic analyses, thin and polished section microscopy, XRF, XRD or spectral imaging The framework for describing the geology and alteration of epithermal deposits includes the following components:

- **Key features of epithermal deposits:** a) commonly associated host rocks, b) the importance of structure, c) the practical chemical and physical constraints, and d) seven must-look-for index fossils.
- **Classic alteration models for epithermal deposits:** generalized, classical lithocap alteration zones, and generalized, classical hypogene zones.
- **Idealized models of alteration in epithermal deposits:** a) the classic Buchanan model, b) the classic high-sulfidation model, and c) the classic low-sulfidation model.
- **The overpressure thrust detachment model**, which emphasizes a) the significance of the soda can model of thrusting, b) the relationships of epithermal deposits to thrust detachment faults, and c) the significance of boiling in listric normal fault splays from the thrust detachment faults.
- **The Carlin-type model**, which follows a) the general characteristics of Carlin-type deposits, b) a magmatic source for gold-bearing hydrothermal solutions, c) a carbonaceous trap that precipitates gold from hydrothermal solutions, d) the formation of Carlin-type deposits at the intersection of source and trap, and e) a generalized model.

The main characteristics of vein or bulk mineable precious-metal epithermal ore deposits are summarized in TABLE 5, which is a duplication of TABLE 1. Note that mineralization can be confined to ore shoots within veins or more generally dispersed in bulk mineable deposits.

TABLE 5. Summary of main characteristics of vein or bulk-mineable precious-metal epithermal ore deposits. *This table duplicates TABLE 1. Descriptions related to Carlin-type deposits are in italics.*

Feature	**Description**
Host rocks	Commonly andesite and rhyolite of Tertiary age. Volcanic rocks are commonly calcalkaline, but alkaline associations are also important. Intrusive and metamorphic rocks are rarely involved. Aquitards that guide hydrothermal fluids, and porous-permeable units able to focus precipitation and host precious metals, can be significant. Breccias are particularly significant because they are porous and permeable, and form—and host ore from—mineralizing hydrothermal fluids; higher grade ores are commonly hosted within epithermal breccias. *Carlin-type deposits, hosted in carbonaceous carbonate rocks (commonly collapsed and decalcified), are arguably a type of epithermal deposit. They are treated as such here*.
Mode of occurrence	Modes include veins, lamellar quartz veins, stockwork, pipes and breccias, disseminations and replacements. Veins are commonly erratically discontinuous and

	tend to be complexly, upwardly branching. *Carlin-type mineralization includes veins, replacement and collapse-dissolution breccia.*
Dimensions	Vertical extents are commonly a maximum of 1000 m, and typically, 200–300 m. Horizontal extents have a maximum of about 3000 m, and typically, 150 to 1000 m in operating mines. Underground mining widths are typically 1–3 m (or more), whereas open pits may mine zones of stockwork or sheeted veins tens to more than 100 m wide. Ore shoots are often horizontally related to a water table, but they can also be cigar or lens shaped of variable orientation. As a rule of thumb, ore shoots within an individual vein commonly involve only one-fifth to one-tenth of the volume of the hosting vein, and the location of the ore shoot is commonly controlled by the intersection of the vein with a crossing structure, which is commonly another vein. The size and shape of ore shoots can be related to dilation related to movement on nonplanar faults.
Structural setting	Structures and breccias may be related to maars and calderas. Regional dilation areas from pull-apart structures are important. Movement on bent faults commonly form openings filled by veins. Quartz flat makes are horizontal veins common to some gold deposits. Thrust detachment zones and related structures—especially listric normal faults—can be significant, and interpretation demands a regional mapping framework. *Carlin-type deposits occur characteristically at the intersection of deep linear faulting associated with intrusive gold sources with a carbonaceous sedimentary hinge-line trap.*
Gangue minerals	Common gangue minerals include adularia, barite, calcite, angel wing calcite, carbonate, fluorite, manganese-wad, pyrite, pyrrhotite, quartz, quartz amethyst, angel wing quartz, quartz (chalcedony or agate), opaline quartz, rhodochrosite, siderite and zeolite. *Carlin-type gangue includes calcite (organic rich and collapse decalcified), quartz, jasperoid quartz and variscite.*
Ore minerals and secondary minerals.	Common ore minerals include acanthite, arsenopyrite, bindheimite, cerargyrite, chalcopyrite, cinnabar, native electrum, enargite, galena, native gold, gold-silver tellurides (and selenides), limonite, marcasite, orpiment, pyrargyrite (proustite), pyrite, pyrrhotite, realgar, scorodite, native silver, sphalerite, stibnite and tennantite-tetrahedrite (freibergite if silver-rich).
Type models	Type models detailed are Buchanan, high-sulfidation, low-sulfidation, Carlin-type and thrust detachment and related structures.
Index fossils for epithermal deposits	Seven index fossils described here are a) adularia, b) amethyst, c) angel wing calcite or quartz, d) black matrix breccia, e) ginguro texture, f) gusano texture in quartz-pyrophyllite lithocap and g) spongy residual-quartz lithocap. *Carlin-type key mineral associations are arsenian pyrite, arsenic-antimony-mercury minerals, phosphate minerals (e.g., variscite) and jasperoid*.

Classic high sulfidation	Goldfield, southwestern Nevada, United States (GF in Figure 34). El Indio, Chile. Yanacocha, Peru (Longo et al., 2010; Teal and Benevides, 2010).
Classic low sulfidation	Mount Skukum, southern Yukon, Canada. Comstock, northwestern Nevada, United States. Round Mountain, central Nevada, United States (RM in Figure 34). Creede, Colorado, United States. McLaughlin, northwestern California, United States. Hishikari, Japan.
Associated deposit types	Intermediate-sulfidation epithermal deposits. Porphyry deposits at depth. Placer deposits. *Carlin-type: low-grade gold in porous/permeable, commonly carbonaceous, or pyritic sedimentary and sedimentary-volcanic rocks.*
Classic thrust–detachment	La Jojoba, northern Sonora, Mexico. Bullfrog, southwestern Nevada, United States (BF in Figure 34).
Classic Carlin	*Carlin, northern Nevada, United States (CR in Figure 34).* *Gold-Quarry, northern Nevada, United States (GQ in Figure 34).* *Cortez, central Nevada (CZ in Figure 34).*

Ten generalized alteration facies related to epithermal deposits, although variable among specific deposits and deposit types, are summarized in TABLE 5, which is a duplication of TABLE 1. Alteration varies markedly between underlying hypogene and surficial lithocap. The ten categories are specifically applicable to low- and high-sulfidation deposits.

TABLE 6. Generalized alteration zones in epithermal deposits.
*Location of precious metal concentrations within these alteration zones are italicized in the table and indicated in the deposit models. Abbreviations: **AB** = albite, **AD** = adularia, **AL** = alunite, **BI** = biotite, **CA** = calcite, **CB** = carbonate, **CI** = cinnabar, **CL** = chlorite, **CP** = chalcopyrite, **EN** = enargite, **EP** = epidote, **GL** = galena, **IL** = illite, **KA** = kaolinite, **MM** = montmorillonite (smectite), **MS** = muscovite/sericite (white micas in general), **PP** = pyrophyllite, **QC** = quartz chalcedony (agate), **QO** = quartz opal, **QZ** = quartz, **SL** = sphalerite, **SS** = sulfosalts, **S*** = native sulfur, **TR** = tremolite, **TT** = tetrahedrite-tennantite and **ZE** = zeolite. Mineral codes are also in TABLES A3 and A4. This table duplicates TABLE 2.*

Code Name	Alteration Name	Key Description	Formation Temperature (approximate; °C)
Lithocap			
STM = **9**	Steam heated	**AL**, **CI**, **KA**, **QO**, **QZ**, **S***. Pervasive and open-space deposition	

SIN = **8**	Sinter	**KA**, **QZ**, **QC**. Rotten, porous, spongy, and commonly bedded silica-carbonate zones. *Low-grade, bulk-mineable precious metals occur*	
ALN = **7**	Alunitic	**AL**, **QC**, **QZ**	
PPT = **6**	Pyrophyllitic and/or kaolinitic	**KA**, **PP**, **QZ**	
Hypogene	~~~~~~~~~~~~~	**Approximate water table (fluctuates)**	~~~~~~~~~~~
BBM = **5**	Bonanza base metal. Sericitic, bonanza high-grade gold and silver and underlying base metal zones	**AD**, **MS** (white micas), **QZ**, **CP**, **GL**, **SL**, **SS, TT, EN**. Often throttle or boiling related. *Commonly precious metal rich with local bonanza, high-grade lodes.*	**Less than** ~350°C
ILT = **4**	Illitic	**IL**, **QZ**, ±(**AD**, **BI**, **MM** [smectite]). *Low grade precious metals occur*	~250°C to ~350°C
MON = **3**	Montmorillonitic (smectitic)	**CL**, **CB**, **MM** (smectite), **ZE**	~150°C to ~220°C
PRP = **2**	Propylitic	**AB**, **CA**, **CB**, **CL**, **EP**, **ZE**	**Less than** ~150°°C
BAR = **1**	Barren	Late and/or early **QZ** and/or **CB** veins	
FRX = **0**	Fresh rock	Unaltered from regional background	

Conclusions on Epithermal Deposits

Framework simplification of the geology and alteration of epithermal deposits presented in this guide does not address many important reviews and details that are published in the extensive literature, some of which are noted in the introduction to epithermal deposits. The guide should, however, provide focus and understanding to field examinations, research, and exploration and development related to epithermal deposits.

Geology/alteration models presented are either revised from historical ones or newly presented here. Specifically, the Carlin-type model is unique but, if correct, has important exploration significance. At the least it should stimulate interest, application, and debate.

'Index fossils' should be kept in mind. They are clues to important features and are not familiar to some geologists. Seven 'index fossils' introduced for epithermal deposits are a) adularia, b) amethyst, c) angel wing calcite or quartz, d) black matrix breccia, e) ginguro habit, f) gusano habit in quartz pyrophyllite lithocap, and g) spongy residual-quartz lithocap.

Final Thoughts on Epithermal Deposits

A background for understanding, describing, mapping, and interpreting the geology and alteration and models related to epithermal deposits is presented in this guide. Key characteristics of relevant features and generalized models are emphasized. In addition, genetic concepts are introduced to provide some logic to the origin of, and relationships among, relevant features.

The practical framework presented in this guide will aid in focused and directed epithermal deposit exploration and evaluation. This will assist with field mapping, evaluation of preliminary exploration data, defining vectors to ore zones, and understanding and evaluating detailed descriptions of deposits by others.

Emphasis in this guide is on features and interpretations related to practical, field-oriented exploration. Some models presented reflect, or are modified by, biases arrived at through the author's own fieldwork. Some explanations will stimulate interest, application, and debate.

This guide is an extension of the introductory guide (Godwin, 2020) *Porphyry and Epithermal Deposits: Mineralization, Alteration and Logging.* This guide introduces features common to epithermal deposits with an emphasis on practical field mapping and exploration methodology. Most general aspects of the geology, hypogene alteration and supergene alteration in porphyry and epithermal deposits are described in this guide. If you have not already done so, I encourage you to read/review it before attempting the challenge of answering the true-false questions in the Epithermal Deposit Problem Set in Appendix C.

I hope you enjoyed this guide, or at least found it useful. May it help you find the big one!

In this guide on epithermal deposits, you will find:

- ➔ **an extension to the introductory guide Porphyry and Epithermal Deposits—Mineralization, Alteration and Logging (Godwin, 2020),**
- ➔ **a background to geology, alteration (including seven significant 'index fossils'),**
- ➔ **a framework for focused deposit exploration and evaluation based on seven deposit models with defined preferred ore locations,**
- ➔ **why Carlin-type deposits occur at the intersection of a magmatic source and a carbonaceous trap, and**
- ➔ **challenges in a problem set.**

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APPENDIX A: SUMMARY OF COMMON CODES USED IN DESCRIBING EPITHERMAL DEPOSITS

Four-Capitalized-Letter Rock Codes for Porphyry and Epithermal Deposits

TABLE A1 is a partial list of four-capitalized-letter rock codes common to porphyry and epithermal deposits. For a more complete listing see Appendix C in Godwin (2020).

TABLE A1: Common rock name codes in porphyry and epithermal deposits (four capitalized letters).
Codes are after Appendix C in Godwin (2020); cf. Blanchet and Godwin (1972).

ADAM = **QZMZ** = adamellite = quartz monzonite	**ANDS** = andesite	**ANOR** = anorthosite
APLT = aplite	**ARGL** = argillite	**BASL** = basalt
BRAN = brain rock with UST texture	**BRXX, BRBM, BRFL, BRVL, BRTO, BRMA** = breccia, ~black matrix, ~fault, ~volcanic, ~tourmalinite, ~magnetite-apatite	**CARB** = carbonate
CHER = chert	**DACT** = dacite	**DIAB** = diabase
DIKE = **DKXX, DKMA, DKQP, DKTO** = dike, ~magnetite-apatite, ~quartz porphyry, ~tourmalinite	**DIOR** = diorite	**DOLM** = dolomite
FELS = felsite	**GABR** = gabbro	**GNES** = gneiss
GOSN = **GOXX, GOEX, GOIN, GOTR, GOSX** = gossan, ~exotic, ~indigenous, ~transported, ~after massive sulfide	**GRAN** = granite	**GRDR** = granodiorite
GRES = greisen	**GREY** = greywacke	**GRNT** = **GRXX, GRFL, GRIN, GRMF, GRUM** = granitic, ~felsic, ~intermediate, ~mafic, ~ultramafic
HORN = hornfels	**IGNM** = ignimbrite	**LIMS, LMSI** = limestone, ~silty
MTVL = metavolcanic	**PORP** = **PPXX, PPDR, PPFL, PPQZ, PPFQ, PPQF, PPMU** = porphyry, ~diorite, ~feldspar, ~quartz, ~feldspar>quartz, ~quartz>feldspar, ~muscovite	**QZDR** = quartz diorite
QZIT = quartzite	**QZMZ** = **ADAM** = quartz monzonite = adamellite	**RHYL** = rhyolite
RYDC = rhyodacite	**SCHS** = schist	**SDVL** = volcanic sedimentary
SEDM = sedimentary	**SHAL** = shale	**SILX** = **QZOT** = silexite = quartzolite
SLSN = siltstone	**SKAR** = skarn	**SYEN** = syenite
TONL = tonalite	**TUFF, TUXL** = tuff, ~crystal tuff	**UNKN** = unknown rock
VLCL = volcaniclastic	**VOLC** = **VLXX, VLAK, VLBM, VLFL, VLIN, VLMF, VLMS, VLTS** = volcanic, ~alkalic, ~bimodal, ~felsic, ~intermediate, ~mafic, ~marine sediment, ~terrestrial sediment	

Three- and One-Capitalized-Letter or One-Number Codes for Epithermal Deposits

TABLE A3 is a partial list of one- and three-capitalized letter comment codes commonly used in descriptions of epithermal deposits. For a more complete listing see Appendix C in Godwin (2020).

TABLE A2: General descriptive codes for epithermal deposits (one -number or one and three capitalized letters).
Codes are after Appendix C in Godwin (2020; cf. Blanchet and Godwin (1972).

ALT = alteration or altered	**AWL** = angel wing habit	**CAP** = capping
COL = colloform habit	**DIS** = **D** = disseminated	**EPD** = epithermal deposit
FBN = flow banded	**GIN** = ginguro habit	**GUS** = gusano habit
HAB = habit or mode of occurrence	**HYD** = hydrothermal	**HYP** = hypogene
LCP = lithocap	**PER** = **P** = pervasive	**PPD** = porphyry deposit
RES = spongy, residual quartz habit	**THR** = throttling	**UNC** = **U** = unconformity
VEN = **V** = vein	**VUG** = vuggy	**WTB** = water table
WTH = weathered	**0** = **FRX** = fresh rock, unaltered	**1** = **BAR** = barren (with either or both pre- and post-mineralization vein)
2 = **PRP** = propylitic (chlorite, epidote, albite, carbonate [calcite], zeolite)	**3** = **MON** = montmorillonitic [smectitic] (montmorillonite [smectite] plus or minus chlorite, zeolite)	**4** = **ILT** = illitic (quartz, illite, plus or minus adularia, biotite, montmorillonite [smectite])
5 = **BBM** = Bonanza base metal with bonanza high grade—commonly throttle or boiling related—underlain by base metal zones (quartz, adularia, muscovite-sericite [white mica], chalcopyrite, galena, sphalerite, sulfosalts [e.g., tetrahedrite-tennantite], enargite)	**6** = **PPT** = pyrophyllitic and/or kaolinitic part of lithocap or hypogene (quartz, pyrophyllite, kaolinite)	**7** = **ALN** = alunitic part of lithocap (quartz, chalcedony, alunite)
8 = **SIN** = sinter part of lithocap that includes rotten, porous, spongy-quartz zone (quartz, chalcedony, kaolinite)	**9** = **STM** = steam-heated part of lithocap (quartz, opal, alunite, kaolinite, cinnabar, native sulfur)	

Two Capitalized-Letter Mineral Codes for Epithermal Deposits

TABLE A4 is a selected list of two capitalized-letter mineral codes common to porphyry and epithermal deposits. For a more complete listing see Appendix C in Godwin (2020)

TABLE A3: Mineral name codes for porphyry and epithermal deposits (two capitalized letters).
Codes are after Appendix C in Godwin (2019; cf. Blanchet and Godwin, 1972).

AA = andalusite	**AB** = albite	**AD** = adularia (K-feldspar)
AH = anhydrite	**AL** = alunite	**AP** = apatite
AS = arsenopyrite	**AT** = atacamite	**AU** = autunite
AZ = azurite	**A*** = native silver	**BA, B^** = barite, ~vein
BI = biotite	**BO** = bornite	**BR** = brochantite
CA, CW, C^, C- = calcite, ~angel wing, ~vein, ~sanded (Carlin)	**CB** = carbonate	**CC, C!, C$** = chalcocite, ~on pyrite, ~on Cu mineral
CH = chalcanthite	**CI** = cinnabar	**CK** = chrysocolla
CL = chlorite	**CP** = chalcopyrite	**CT** = cassiterite

CU = cuprite	**CV** = covellite	**CY** = clay
C* = native copper	**DG** = digenite	**DK** = dickite
DU = dumortierite	**EL** = electrum	**EN** = enargite
EP = epidote	**FD** = feldspathoid	**FL** = feldspar
FM = ferrimolybdite	**GL** = galena	**GR** = graphite
G* = native gold/electrum	**HE, HS** = hematite, earthy, ~specular	**HB** = hornblende
IL = illite (hydromuscovite)	**JA** = jarosite	**KA** = kaolinite
KF = K-feldspar (orthoclase)	**LI** = limonite	**MC** = malachite
MI = mica	**MG** = magnetite	**MM** = montmorillonite (smectite)
MN = manganite/alabandite	**MO** = molybdenite	**MR** = marcasite
MU, MS, ML, MY = muscovite (white mica), ~sericite, ~lepidolite (purple from lithium), ~(yellow from fluorine)	**NE** = nepheline	**NO** = neotocite
OQ = opaques	**OP** = orpiment	**OX** = oxides
PE = pyrolusite	**PH** = phlogopite	**PL** = plagioclase
PO = pyrrhotite	**PP** = pyrophyllite	**PT** = petroleum
PW = powellite	**PX** = pyroxene (commonly augite)	**PY, P^, P#** = pyrite, ~vein, ~boxwork
QZ, QA, QB, QC, QH, QJ, QO, QR, QS, , Q^ QW= quartz, ~amethyst, ~brain (**UST**), ~chalcedony, ~high temp (square-cristobalite), ~jasperoid, ~opal, ~rutilated (blueish), ~smoky (often from radiation) , ~vein, ~angel wing)	**RH** = rhodochrosite	**RE** = realgar
SB = stibnite	**SC** = scorodite	**SL** = sphalerite
SS = sulfosalt	**SU** = sulfate	**SX** = sulfide
S* = native sulfur	**TB** = torbernite	**TE** = telluride
TN = tenorite	**TO** = tourmaline	**TR** = tremolite
TT = tetrahedrite-tennantite	**TU** = turquoise	**VA** = variscite
WD = wad	**WO, WF, WH** = wolframite, ~ferberite, ~hubnerite	**ZE** = zeolite

APPENDIX B: LOGGING PROCEDURES AND FORMATS FOR EPITHERMAL DEPOSITS

Logging Techniques for Describing Diamond Drillholes in Epithermal Deposits

Best practice for common procedures in diamond drill hole logging goes a long way to satisfying increasingly stringent quality-assessment (QA) and quality control (QC) requirements of regulatory agencies. Of course, the presented logging formats helps with this too. The following are some organizational hints for logging diamond drill hole core.

- **Drillhole names** are conveniently labeled: project, year, type and number of the hole (e.g., ING14DD012 or Prj/Yy/Tp/Num where: Prj = three letters for project name [ING]; Yy = last two numbers of the year 20[14]; Tp = type where DD = diamond drill hole, OC = outcrop, RC = reverse circulation, RB = reverse air blast, TR = trench and Num = number of the drillhole [012]). Note that this suggested convention is concise, easily interpreted, and convenient for digital sorting by project, year, type, and number.
- **Core layout in core boxes** should mimic how one reads a letter: left to right, left to right, etc. Although obvious, I have seen junior drill helpers put the core in the box like a snake going from left to right and then right to the left. Check carefully, especially at the beginning of a program.
- **Drillhole deviations** as measured by downhole surveys, must be recorded separately from the drill logging forms presented here. If downhole survey data is lacking, hole deviations sometimes can be estimated. Vertical holes tend to deviate less than inclined holes. When plotting drill holes with geographical information systems (GIS), the deviation information is critical and facilitates accurate plots (e.g., cross-sections).
- **Build a core library** consisting of several core boxes that hold typical examples of various rock and alteration types. One can include field specimens as well as the core. These can be used for reference to help with consistent descriptions for yourself and other loggers/mappers during the current and subsequent programs. It is also compact and available for future detailed study, as required.
- **Compressed or skeletonized drillholes** are made by taking a representative sample of core from each assay interval and labelling and putting it in a separate core box. These are appropriate, especially for porphyry deposit logging, where assay intervals are constant. Because the compressed or skeletonized holes occupy only a few core boxes compared to the whole core, they help with quick review and are readily stored and transported for future study. In porphyry deposit logging, generally, look at the interval being described and pick out a core piece that looks to be characteristic of that interval. Use its properties to make entries in the log, sometimes with the aid of a binocular microscope, a needle to scratch, acid to detect carbonate and other field identification tools. One can then put the same specimen into a compressed log core box. Finally, insert a label (generally a driller's block notated with a carpenter's graphite pencil) in the original core box, noting specimen removal.
- **Core box photography** is a vital record. The core should be photographed and logged before it is split, but intervals to be assayed should be tagged with assay labels. After tagging, one can photograph core boxes stacked in order, four at a time, on an inclined board. Using daylight, a handheld camera positioned at right angles from the centre of the assembled core boxes is usually adequate. The core should be unsplit, cleaned and wet, so textures become clearer. Include a scale and a colour format for more accurate future size and colour estimations. In addition to a standard record, some features can be recovered later if needed from the photos. Recoverable features include a) estimations of geology and alteration, b) core recovery and general nature of the core, and c) rock-quality designation. Both core recovery and rock-quality designation can be helpful in geotechnical assessments of rock stability in mining. Core recovery is the percentage of solid pieces of rock core. Rock-quality designation is a rough measure of the degree of jointing or fractures in the core, measured as a percentage of the drill core in lengths of 10 cm or more (the 10 cm rule can be modified for core of different diameters).
- **Core sampling** is the most important corporate objective. Core is split or sawn in half. Sometimes it is necessary for the geologist to dictate how core is sampled by drawing lines along the centres of appropriately rotated core. The half-split of the core interval to be analyzed is bagged, along with the appropriate assay tag; a duplicate part remains in the core box. Books of essay tags, available from assayers,

are made of resistant paper, such as Tyvek®. Assay books have tags with a unique number sequence. Each tag has the same number on the book stub and two rip-off copies. For each tag: a) the assay stub is notated with drill hole number and from–to information, b) one rip-off tag is inserted in the sample split to be sent to the assay laboratory, and c) the remaining rip-off tag is affixed to the core box at the start of the assay interval sampled. The assay books with notated stubs must be retained for backup information and potential quality control (QC), and quality assurance (QA). Specimens removed for the core library, compressed logs or detailed study must be marked by pencilled notation on wooden drillers' block as removed. The removed specimen must be from the half-split core that stays in storage, not from the core sent for analysis. When metallurgical tests are likely to be required, it can be essential to protect samples and core from oxidation.

- **Logging formats in Figures B1 and B2** can also accommodate detailed descriptions of trenches or along surfaces of outcrops. Doing so provides compatible formats of all drill, trench or outcrop detail that facilitate digital display. For example, a surface trench or outcrop can be shown on a drill section as a sub-horizontal detail, along with underlying drill holes. Likewise, deflections in trench direction can be treated the same as drill hole deviations.
- **Describing geology, alteration and structure in core** is best done on the cleaned whole core before it is split. Structural angles, especially, are more easily measured (oriented core is sometimes required). Textures and rock types generally are best identified on whole core when it is wet. Alteration mineralogy is more easily recognized on the dry core. Typically, a series of boxes are laid out in order on the ground outside in daylight, but a logging table with good light is required for big projects. Measured core recovery and rock-quality designation must be made on the core before it is split and can often be done and recorded by an assistant. When beginning to log core, use flagging tape (several colours for different types of features) to mark a) zones: casing, overburden, lost core, supergene types, oxide, hypogene; b) rock type: major lithological contacts, significant textures; c) structures such as significant faults, bedding, axial plane cleavage and timing relationships, which can also be recorded on the graphic log; and d) mineralization and alteration: changes in percentages of individual minerals, broad changes in alteration style, significant habits or mode of occurrences. The core is then described systematically on the logging form. Detailed descriptions are commonly based on pieces of core picked out as representative of the interval being described. A hand lens, scratch needle tests, a hand magnet, 10% HCl acid and a binocular microscope can be helpful. Specimens can be put aside for the core library and additional detailed examination of specific gravity, thin sections, X-ray diffraction (XRD) element analyses and shortwave infrared (SWIR) mineral determinations. When logging in detail, the location of the original divisions marked by the flagging tape commonly needs to be moved. One can only achieve meaningful statistics relating geology and alteration to assay information if the logging descriptions match the assay intervals —if it is worth assaying, it is worth describing!
- **Permanently marking drillhole collar locations in the field** is essential so one can relocate them—sometimes years later. A common way is to put a box, approximately 10 cm deep and 30 cm square, over the hole. Fill this with concrete and scribe the whole number into the top of the cement slab while it is wet. Note that the labelling system for holes recommended here (Prj/Yy/Tp/Num) identifies the project, year drilled, type of drill hole and hole number for that project and year. This labelling method is usually sufficient, but additional information can be added as desired. One should plug the top of the to inhibit erosion that might displace the concrete marker slab. In some areas and instances, holes must be backfilled because of environmental concerns.
- **Core storage** is important, but expensive. Given the cost to obtain 1 m of core, it is evident that core must be available for later reference. Methods on how to construct core racks are available elsewhere. However, in Canada, porcupines eat wooden core boxes because they are attracted to the plywood glue; in Africa, termites eat wooden core boxes; plastic becomes brittle, particularly if exposed to the sun. Label boxes well with labels that will last. Thin aluminium labels that can be scribed with a ballpoint pen are commonly used.
- **Instrumental data that can be systematically collected** with handheld instruments and added to drill logs include magnetic susceptibility and conductivity of core; average spot scintillometer readings for U, Th and K; SWIR spectral analysis for minerals in the core; and handheld XRF element analyses. Ultraviolet scanning in short and long wavelengths is appropriate in some instances but be aware that without careful scrubbing of the core it is difficult because modern organic drill mud additives commonly fluoresce. This additional data can aid in the interpretation of geophysical, geological and alteration features.

- **Record of core recovery, rock-quality designator (RQD) and intervals assayed** can be done while organizing the core (by an assistant, if available) before logging. At the same time, tagged assay intervals should be established and recorded. A geologist's input will be required if this is not a systematic length, as is good practice for porphyry deposits. These are simple marking and measurement skills that relate to distance blocks inserted by the drillers. New assistants must be taught how to fill out this record. And the data must be systematically recorded with an ink pen as a separate record in a bound book with lined and prenumbered pages that cannot be removed (i.e., loose-leaf records are not acceptable). Errors in this record should be marked (crossed out, so the original is still readable) and the revisions rewritten (i.e., no erasing or whiteout). This book, and the books of notated assay stubs, are essential records for potential QC and QA examination. Headings in this record, modified as appropriate, should include Date, HoleName, FromToMetres, AssayTagNumber, MeasuredRecovery%, RockQualityDesignation% (RQD, if required), LabSentTo, DateSent and Remarks. This handwritten record is critical; relevant information from this record can be digitally entered as part of the total drill hole record (e.g., hole number, from–to, geology, recovery, RQD, assay tag numbers).

Formats for Describing Diamond Drillholes, Trenches, and Outcrops in Epithermal Deposits

Modification of logging formats (Figures B1 and B2) is necessary to capture features that are unique to specific porphyry deposits and different types of porphyry deposits. Changes should accommodate detailed descriptions of drill holes, trenches and along surfaces of outcrops. Doing so provides compatible formats of all drill, trench or outcrop detail that facilitate digital display. For example, a surface trench and outcrop can be shown on a drill section as a sub-horizontal detail, along with underlying drill holes. Note that deflections in trenches or outcrop can be treated the same as drill hole deviations.

All logging formats presented here have a common first page and simplified following pages (Figures B1 and B2). The first page has header information describing drill hole type, location, and the date drilled. Under the heading is the format for the description of the rocks and alteration. The following pages duplicate only the rock and alteration part of the first page. Header details are described in TABLE B1. The log sheet has a logical and universal sequence that is, from left to right:

1. A graphic log to enable capture of features difficult to code (e.g., crosscutting structures), and especially if coloured, to facilitate visual interpretations,
2. General specification of what one is looking at in terms of 'zone' (e.g., capping, supergene oxide, supergene sulfide, hypogene),
3. From–to interval described,
4. Rock-type and its characteristics,
5. Structures superimposed on the rock type,
6. Alteration and mineralization superimposed on the rock type,
7. Optional interpretation of overall alteration/mineralization facies for interval and
8. Written comments for important features not already captured (the codes in this appendix facilitate compact descriptions).

One is, therefore, going from noting what/where one is at, to what is the basic rock type, to what is superimposed upon the rock type, to comments. These descriptions should always be together. Because, for example, it is challenging to identify alteration features without knowing what is altered. Rock type mineralogy must be known before one can determine superimposed alteration mineralogy.).

Data entry can be done directly on a laptop or in paper forms like those presented here for subsequent data entry. One advantage of using direct computer entry into a program like Microsoft Excel (or Microsoft Access) is that entries can be controlled for consistency by making only agreed-upon codes allowable. Nevertheless, many prefer recording with an HB pencil on letter-sized paper, landscape orientation, carried in an open clipboard with either a leather pouch or a ledge glued to the clipboard for holding:

- A 0.7 mm HB mechanical pencil,
- A stick eraser,

- A hardness scratcher made by putting a fine needle in a 0.7 mm mechanical pencil,
- A pencil stud finder magnet, and
- Any other pertinent diagnostic tools.

On a paper format log, one can easily erase, and change entered information. More importantly, one can sketch on and colour a graphic log, which is especially valuable as an effective display that records a) structural and relative timing information or b) highlights geology, alteration, and specific mineralization. The graphic log provides an instant strip-log for the hole that can aid in visualizing the geology.

DdLogEpi 18DdLogEpith.docx CODE: N–*n*il, T–*t*race, L–*l*ow, F–*f*air, B–*b*elow med, M–*m*edium, A–*a*bove med., H–*h*igh, V– *v*ery high, X–e*x*treme, Y–*y*es|total, O–*o*bserved *Ent_ Page 1 of ___*

HoleID (PrjYyDdNnn): _ _ _ **18DD** _ _ _	Collar **AzimuthUTM**: _______ [degrees]	**Project**: ______________ Porphyry Copper	**DrilledBy**: ____________________________
Collar **Easting**: _______________ m	Collar **Dip**: ____________ [+ down]	**SurveyDownHole** [circle]: yes no [see form]	**DateDdStarted**: [YyMmDd]: 18- _ _ - _ _
Collar **Northing**: _______________ m	Hole **TotalDepth**: ___________ [m]	**GridType**: UTM ____________________	**LoggedBy**: __________________________
Collar **Elevation**: _______________ m	**HoleSizes**: _______ ______ ______	Property Grid Line: ____________________	**DateLogStarted**: [YyMmDd]: 18- _ _ - _ _

Gra-phic STR ALT	**Gra-phic ROC MIN**	**HoleID** _ _ _ **18 Zone**	**From m Fac1**	**To m Fac2**	**SamNo** [link to assays] **Value**	**Rock1 & %** [4-letter] **Rock2 & %**	**Min1** [2-code] **Min2**	**Qual1** [grn size, 3-letter] **Qual2**	**Struct1 Type Angle** 90°CA **Struct2**	ALTERATION & MINERALIZATION **QZ AD PP AL CL CA PY MN F1** **QC MS KA MM EP SD CP LI F2**	**General Comment** _____ _____ **GeologyNotes (2 lines)**
		DD									
		DD									
		DD									
		DD									
		DD									
		DD									
		DD									
		DD									
		DD									
		DD									

DdLogEpi (cont) CODE: N–nil, T–trace, L–low, F–fair, B–below med, M–medium, A–above med., H–high, V– very high, X–extreme, Y–yes|total, O–observed *Ent Page __ of ___*

Gra-phic STR ALT	**Gra-phic ROC MIN**	**HoleID** _ _ _ **18 Zone**	**From m Fac1**	**To m Fac2**	**SamNo** [link to assays] **Value**	**Rock1 & %** [4-letter] **Rock2 & %**	**Min1** [2-code] **Min2**	**Qual1** [grn size, 3-letter] **Qual2**	**Struct1 Type Angle** 90°CA **Struct2**	ALTERATION & MINERALIZATION **QZ AD PP AL CL CA PY MN F1** **QC MS KA MM EP SD CP LI F2**	**General Comment** _____ _____ **GeologyNotes (2 lines)**
		DD									
		DD									
		DD									

Figure B1. Example of logging format, page 1 and continuing pages, for a diamond drill holes, trenches and outcrops in an epithermal deposit environment.
Page 1 differs from page 2 because only page 1 has an extensive header that defines features common to the whole hole. Codes in TABLES B1 and A1 to A3 define and specify how to record entries.

General codes and formats for recording detailed data for porphyry deposits in drill cores, drill chips, trenches and outcrops are in TABLES B1 and B2. The example drill log formats in Figures B1 and B2 are generally applicable to epithermal deposits. However, all headings are easily modified to describe better the specific deposit being studied. For computer/statistical analysis, one must consistently describe geological and alteration descriptions to match assay intervals, regardless of the logging method. Note that in mapping detail at a deposit scale, it is appropriate to map surface trenches and relevant outcrops in the same way as drill holes. For example, a surface trench or outcrop can be described as an approximately flat diamond drill hole. Survey information for all of these can be defined the same way. Detailed information from the surface trenches then becomes compatible with data from the diamond drill holes during computer-assisted analysis, such as the generation of cross-sections.

RcLogEpith 18RcLogEpith.docx CODE: **N** *n*il, **T** *t*race, **L** *l*ow, **F** *f*air, **B** *b*elow med., **M** *m*edium, **A** *a*bove med., **H** *h*igh, **V** *v*ery high, **X** extreme, **Y** *y*es!total, **O** *o*bserved ***Ent __ Page 1 of ___***

HoleID (PrjYyRcNn): _ _ _ **18RC** _ _ _	Collar **Azimuth**: [degreesN-UTM]	**Project**: ____________ Porphyry	**DrilledBy**: ____________
Collar **Easting**: ____________ m	Collar **Dip**: ________ [+ down]	**SurveyDownHole** [circle]: yes[see form] no	**DateDdStarted**: [YyMmDd]: 18 - _ _ - _ _
Collar **Northing**: ____________ m	Hole **TotalDepth**: ________ [m]	**GridType**: UTM ____________	**LoggedBy**: ____________
Collar **Elevation**: ____________ m	Hole **Diameter**: RC ________ cm	Comment: ____________	**DateLogStarted**: [YyMmDd]: 18 - _ _ - _ _

Gra- phic Log	**Gra- phic Log**	**LOG _ _ _ 18 Zone**	**FRM m AgGt**	**TO m AuGt**	**ASSAY SamNo Cu%**	**WetDry Pb%**	**Recov Zn%**	**ROCK Rock1&% Rock2&%**	**ALTERATION & MINERALIZATION QZ AD PP AL CL CB LI QC MS KA MM EP PY Z1**	General comment in this box **Notes [2 lines]**
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								
		RC								

RcLogEpith (cont.) CODE: **N**=*n*il, **T**=*t*race, **L**=*l*ow, **F**=*f*air, **B**=*b*elow med., **M**=*m*edium, **A**=*a*bove med., **H**=*h*igh, **V**= *v*ery high, **X**=extreme, **Y**=*y*es!total, **O**=*o*bserved ***Ent___ Page____ of___***

Gra- phic Log	**Gra- phic Log**	**LOG _ _ _ 18 Zone**	**FRM m AgGt**	**TO m AuGt**	**ASSAY SamNo Cu%**	**WetDry Pb%**	**Recov Zn%**	**ROCK Rock1&% Rock2&%**	**ALTERATION & MINERALIZATION QZ AD PP AL CL CB LI QC MS KA MM EP PY Z1**	General comment in this box **Notes [2 lines]**
		RC								
		RC								
		RC								

Figure B2. Example of logging format, page 1 and continuing pages, for a reverse circulation drill log in an epithermal deposit environment.

Page 1 differs from page 2 because only page 1 has an extensive header that defines features common to the whole hole. Codes in TABLES A1 to A3 and B1 define and specify how to record entries.

TABLE B1. Explanation of logging formats related to epithermal deposits. *Information is related to logging formats in Figures B1 and B2.*	
Entries in form	**Explanation**
Header information *Page 1 only. Basic information required in QA and QC control*	The header information at the top of page 1 is standard information for drill holes. It includes hole name, location and grid type, inclination, depth, who drilled and who logged the hole, whether the data has been entered into computer files, etc.
Hole ID *Embeds a lot of information and allows logical sorting*	Hole identification is ordered to facilitate sorting by project, year, type and number of the hole. E.g., GLD18DD005 describes the log in an organized way suitable for systematic sorting. The interpretation of this name is as follows a) the project in three letters [GLD for the Golden Project], b) the year in two numbers [18 for 2018], c) what is being described in two letters [DD for diamond drill hole, OC for outcrop, RB for reverse air blast; RC for reverse circulation; TR for trench, etc.], and c) the drill hole sequence in three numbers [005]. Alternating alphabetic symbols with numbers enhances readability.
Description titles *Logically from: graphic → zone → from-to → rock ± structure → alteration → notes*	Description titles on Page 1 below the header and at the top of each additional page are the same. These titles describe the two-line groups for the data to be entered in every form. Column entries enhance consistency in observation and facilitate subsequent computer statistical analysis. As an example, statistical correlations can be determined among a) visually estimated sericite (MS), b) visually estimated pyrite (PY), c) visually estimated chalcopyrite, and d) assayed copper percentages. All such factors can also be plotted on strip logs and in three dimensions. These plots facilitate the discovery of alteration zoning, pyrite haloes and ore shells, to name a few possibilities.
Graphic ALT STR Graphic MIN ROC *Hand drawn/coloured*	The graphic log for sketching by hand is in the first two columns. Use can vary, but column 1 might be assigned alteration and structure, and the second column mineralization and rock type. Timing/crosscutting relationships are most easily captured graphically. Colouring of the graphic log (and or mineral columns) enhance visual interpretations.
Zone *Basically what one is looking at*	Zones are commonly **CAP** = cap; **DIS** = disseminated; **HYP** = hypogene; **SUO** = supergene oxide; **SUS** = supergene sulfide; **SUL** = sulfide; **STK** = stockwork and **TRS** = transition. Zones are modifiable as required.
From and To *Where you are at*	From–To description; note that this interval is commonly constant in porphyry/bulk mineable deposits (e.g., 1.5 or 2.0 m). Thus, in porphyry deposits the log form has a constant scale. However, a constant scale is not appropriate in logging all deposits. For example, variable From - To distances would be used for vein deposits where there might be long intervals of a constant rock with characteristic alteration

	and shorter intervals of significant alteration and veining where detailed information is needed. Always sample/assay intervals must have matching geological/alteration descriptions.
SamNo *Key to future assays*	Sample number of assay tags used for intervals assayed/analyzed; facilitates merging of analytical information later for statistical and geographical information system analysis/display of all assay and logged data.
Value Can be *added later if logs are used manually*	If desired, values of assays can be added to the logs after analysis. This can aid visual interpretations from original logs. This facilitates checking assay information against recorded mineralogy. For example, one would expect the copper assay to agree with the abundance of copper minerals (e.g., chalcopyrite = **CP**, bornite = **BO**, etc.).
Rock1 and **%** **Rock2** and %	For every interval, two rock types can be entered. The percentages of each are recorded. For example, **MONZ** 80, **DYKE** 20 for an interval of 80% monzonite and 20% dyke. Additional rock complexities can be noted in comments and the graphic log.
Min1, Min2	Two qualifying minerals for the rock can be entered (e.g., biotite = **BI**; hornblende = **HB**), where **Min1** is generally in greater quantity or more important than **Min2**.
Qual1, Qual2	Two qualifying textures or characteristics for the rock can be entered (e.g., **FGR**, **MGR**, **CGR** = fine, medium, coarse grained; **SCV** = shatter cleavage; **UST** = unidirectional solidification texture).
Struct1, Struct2 type Angle measured from 90° to core axis	Two structures—**Struct1**, **Struct2**—can be defined (e.g., B = bedding; F = fault; **V** = vein), plus the angle *perpendicular* to the core axis (e.g., **V 42**, **F 26** for a vein 42°, and a fault 26° to the core-axis perpendicular). Note that in a vertical hole, measuring angles with respect to the perpendicular of the core axis, is the same as a dip measured at surface.
ALTERATION and MINERALIZATION GANGUE/ORE % *Generally ordered logically from high to low intensities*	Alteration and mineralization can be systematically recorded. Minerals (two-capitalized-letter codes) will change to correspond to specific projects. Common ones entered here as examples are: **QZ** = quartz; **KF** = K-feldspar; **BI** = secondary biotite; **MS** = muscovite sericitic; **CY** = clay; **CB** = carbonate; **PP** = pyrophyllite; **CL** = chlorite; **EP** = epidote; **XX** and **YY** = other minerals entered as two letters, or if unknown **WW**, **XX**, **YY** and **ZZ**; and **LI** = limonite; **MO** = molybdenite; **BO** = bornite; **CP** = chalcopyrite; **PY** = pyrite; **MG** = magnetite; **HS** = hematite-specularite; **LI** = limonite; **GO** = goethite; **JA** = jarosite. Ore and gangue minerals should be organized from left to right, generally following mineralogy of decreasing facies.

APPENDIX C: EPITHERMAL DEPOSIT PROBLEM SET

C1: Regional Geology of Epithermal Deposits

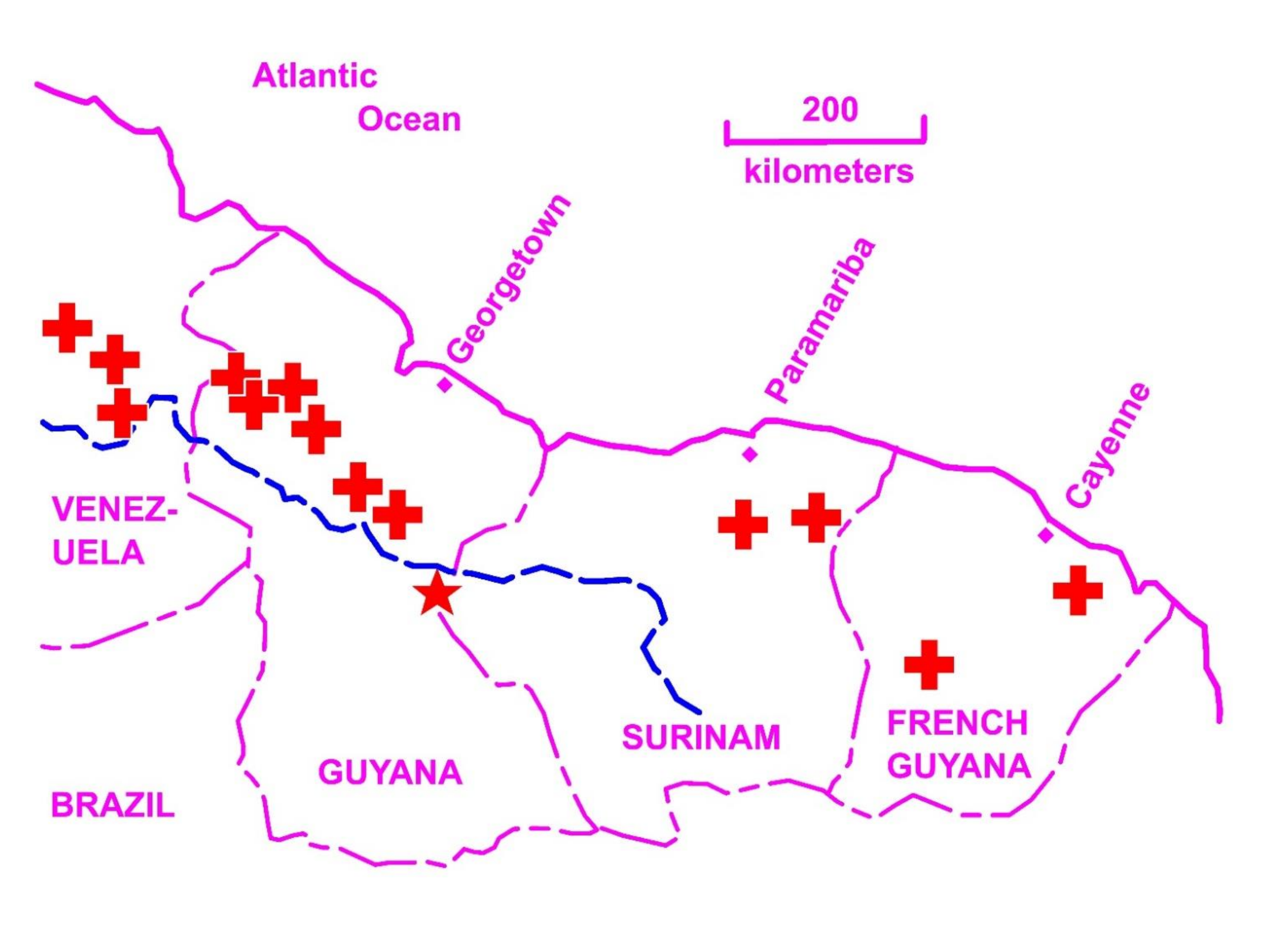


Figure C1. Berbice property with respect to the regional, northwest-trending gold belt in the Guyana Shield. *The Berbice property is in Guyana and is marked with a red star. Red plusses: major gold deposits, blue dotted line: approximate southwestern limit to major gold deposits in the Guyana Shield. Regional map is simplified from a map in the NI 43-101 Technical Report on the Toroparu Gold Project, Guyana, for Sandspring Resources Ltd, by SRK Consultants (May 2013).*

Question C1-1 (6 marks): Berbice property, Guyana.

The Berbice property (red star in Figure C1) was submitted for option. Mark each statement as true (**T**) or false (**F**):

1. The property is not in the gold belt of the Guyana Shield. ___
2. The property is in South America. ___
3. Major placer and gold deposits are not nearby. ___
4. The famous Cristinas property in Venezuela is not in the same belt. ___
5. The property is in the Guyana Shield. ___
6. The property is in Africa. ___

C2: Mineralogy

Figure C2. Vein from Bald Mountain Wash prospect, central Nevada, United States (BM in Figure 91). *Picture width is about 6 centimetres.*

Question C2-1 [10 marks]: General mineralogy and habits.

Referring to Figure C2, mark each statement as true (**T**) or false (**F**):

1. This is a quartz vein. ________
2. This is a calcite vein. _______
3. The specimen has comb texture. ______
4. Specimens like this never have gold. _______
5. The fragments in the specimen indicate that the vein is in a fault. ________
6. The specimen has vugs. ______
7. The specimen displays colloform texture. _______
8. The specimen originally contained sulfides. ______
9. The limonite on the specimen indicates that it contained arsenic minerals. _______
10. Specimens like this always have gold. ________

Question C2-2 [110 marks]: Mineralogy of zones.

In TABLE C1, pick four minerals (mark only four as true [**T**], the rest as false [**F**] in each column) to match each column description.

TABLE C1. Minerals associated with specific zones in epithermal deposits.

MINERAL	Four ore zone silicates low sulfides	Four ore zone silicates high sulfides	Four minerals steam-heated lithocap	Four minerals lithocap below sinter	Four ore zone sulfides
Quartz					
Muscovite					
Chlorite					
Native sulfur					
Epidote					
Alunite					
Pyrophyllite					
Illite					
Montmorillonite (smectite)					
Chalcedony					
Carbonate					
Opal					
Kaolinite					
Adularia					
Pyrite					
Tetrahedrite (tennantite)					
Enargite					

Tellurides					
Native gold **Native silver Electrum**					
Stibnite					
Galena					
Sphalerite					

Question C2-3 [25 marks]: Pathfinder minerals.

Pick best ten 'pathfinder minerals' (mark ten as true [**T**], and the rest false [**F**]) associated with major Carlin-type deposits:

1. Quartz ______
2. Chalcopyrite ______
3. Galena ______
4. Pyrite ______
5. Sphalerite _____
6. Orpiment ______
7. Wollastonite _______
8. Cinnabar ______
9. Actinolite _______
10. Variscite ______
11. Hornblende ______
12. Realgar ______
13. Epidote ______
14. Chlorite ______
15. Bornite ______
16. Arsenopyrite ______
17. Graphite ______
18. Scorodite ______
19. Petroleum ______
20. Barite ______
21. Turquoise ______
22. Torbernite ______
23. Augite ________
24. Garnet ________
25. Spodumene ______

Question C2-4 [10 marks]: Mineral zoning.

For each set of two assemblages, label the one closest to the vein '**C**', and the one more likely to be more distant from the vein '**D**':

1. Kaolinite, montmorillonite (smectite) _______ , versus quartz, adularia, illite _________
2. Quartz, muscovite, illite _______ , versus chlorite, epidote _________
3. Quartz, alunite _______ , versus quartz, native sulfur _________
4. Quartz, chalcedony _______ , versus muscovite, illite, adularia _________
5. Quartz, jasperoid _______ , versus sanded carbonate _________

C3: Rock Types Related to Epithermal Deposits

Question C3-1 (6 marks) Carlin-type deposits in carbonaceous rocks.

Carbonaceous rocks can be important because; mark as true [**T**] the two best answers:

1. They are generally soft and easy to mine. _____
2. They often contain pyrite that can be replaced by gold _____
3. They often contain valuable phosphate deposits _________
4. They are a good guide to discovery of uranium __________
5. Gold-bearing hydrothermal solutions can be reduced to native gold by the oxidation of carbon _____
6. They are a good source of vanadium ______

Figure C3. Breccia from the El Corazon epithermal gold property, Western Cordillera, Ecuador. Photo is of an underground exposure.

Question C3-2 (6 marks): Breccias in epithermal deposits.

Figure C3 shows a rock interpreted here as a quartz-silicified breccia; however, it has also been interpreted as a siliceous lithocap. How does one distinguish the difference? Mark the three best answers (as true [**T**]) that indicate it is likely a hydrothermal breccia and not a siliceous lithocap.

1. The rock is not spongy. _____
2. The rock is almost all quartz. _____
3. Fragments are distinct. _____
4. The rocks are resistant; consequently, outcrops stick up at surface. _____
5. Mapping and drilling indicate a deep, pipe-like geometry. _____
6. The rock commonly contains significant gold. _____

Figure C4. Breccia from the El Corazon epithermal gold property, Western Cordillera, Ecuador.
Photos are of underground exposures.

Question C3-3 (5 marks): Breccias in epithermal deposits.

Figure C4 is a photo of a classic hydrothermal breccia because (mark statements as true [**T**] or false [**F**]):

1. Some of the fragments are mafic. ____
2. The limonite stain indicates mineralization. ____
3. There are distinct fragments within a finer matrix. ____
4. The rock looks like concrete. ____
5. There are different fragment types. ____

Figure C5. Breccia from the El Corazon epithermal gold property, Western Cordillera, Ecuador.
Photo is of an underground exposure.

Question C3-4 (5 marks): Breccia in epithermal deposits.

Figure C5 shows an underground exposure of breccia that illustrates some particularly important features. Check the three most significant observations in the following (mark statements as true [**T**] or false [**F**]):

1. There are distinct fragments surrounded by a finer matrix. ____
2. There are two styles of breccia, indicating two brecciation events. ____
3. The rock looks like concrete. _____
4. Part of the breccias has a black matrix, which is an index fossil for epithermal deposits. _____
5. The fragments are angular. ______

Figure C6. Breccia from the El Corazon epithermal gold property, Western Cordillera, Ecuador.

Question C3-5 (5 marks): Breccia in epithermal deposits.

Some features of the breccia in Figure C6 are important. Please mark the following statements as important: true (**T**), or not important: false (**F**):

1. The veins cutting the breccia are subparallel. _____
2. The breccia is made mainly of quartz. ______
3. The veining indicates an additional, superimposed mineralizing event. _____
4. The breccia is cut by sulfide veins. ______
5. The breccia is cut by quartz veins. ______

Figure C7. Breccia from the El Corazon epithermal gold property, Western Cordillera, Ecuador.
Photo of drill core is about 3 centimetres high.

Question C3-6 (5 marks): Breccia in hydrothermal deposits.

The breccia in Figure C7 has an angular fragment (left-centre of photo) that has conspicuous quartz eyes. State whether the following statements are true (**T**) or false (**F**):

1. The fragment is probably andesite. _____
2. The fragment is probably porphyritic rhyolite. _____
3. The fragment is mineralized. _____
4. The breccia likely formed from explosion of a porphyritic intrusion. _____
5. The fragment is pre-veining. _____

C4: Structures and Tonnages in Epithermal Deposits

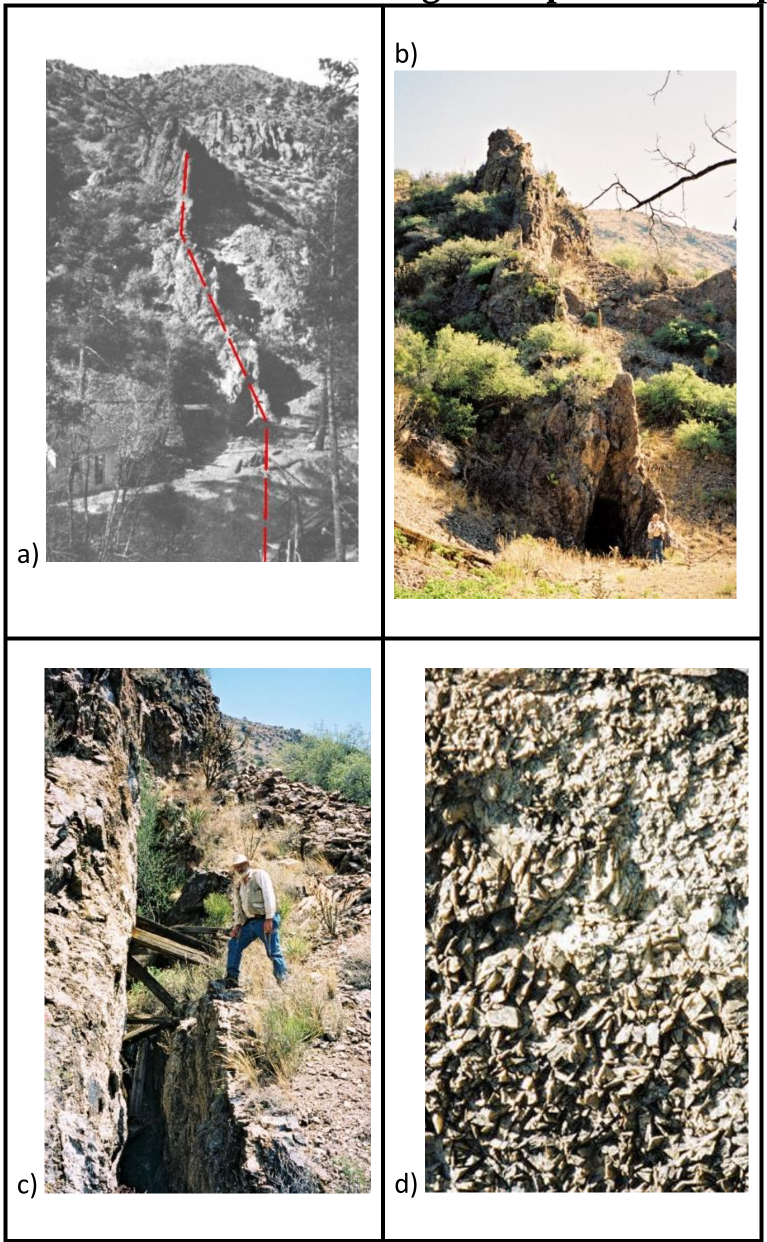


***Figure C8. Pankey gold vein in New Mexico, United States. a)** Historical photo shows the mined vein in the central portion of the fault marked by a red, dotted line. **b)** Current overall view of vein. **c)** The vein width mined is about 1 metre.The part of the vein that was mined is about 100 metres long. **d)** Whorls are about 1 centimetre long.*

Question C4-1 [2 marks]: Pankey vein.

Given that the mined portion of the Pankey vein is in the central portion of the fault trace marked in red in Figure C8a, is the fault (mark statements as true [**T**] or false [**F**]):

1. Right handed? _____
2. Left handed? _____

Question C4-2 [5 marks]: Pankey vein.

Assuming from Figure C8a to c that the productive vein was 1 m wide with a stated length of about 100 m, the approximate potential tonnage mined, if no pillars were left and that the depth was half the stated length (mark statements as true [**T**] or false [**F**]) is:

1. 125,000 tonnes _____
2. 12,500 tonnes _____
3. 25,000 tonnes _____
4. 250,000 tonnes _____
5. 500,000 tonnes _____

C5: Textures

Question C5-1 [10 marks]: Pankey vein.

The texture in Figure C8d is (mark statements as true [**T**] or false [**F**]):

1. Taber ice texture ______
2. Cuneiform shrinkage crack texture ____
3. Angel wing texture ______
4. From ice imprints ______
5. Laminar texture ______
6. Not significant ______
7. An important index fossil for epithermal deposits ____
8. Lattice texture ______
9. Lath texture ______
10. A texture that forms outside of a vein _____

Question C5-2 [5 marks]: Pankey vein.

The texture in Figure C8d indicates (mark answers as true [**T**] or false [**F**]):

1. Degassing of carbon dioxide when it was formed. _______
2. The water table level when it was formed. ____
3. Absence of gold when it was formed. _______
4. Boiling when it was formed. _______
5. Potential gold mineralization when it was formed. _______

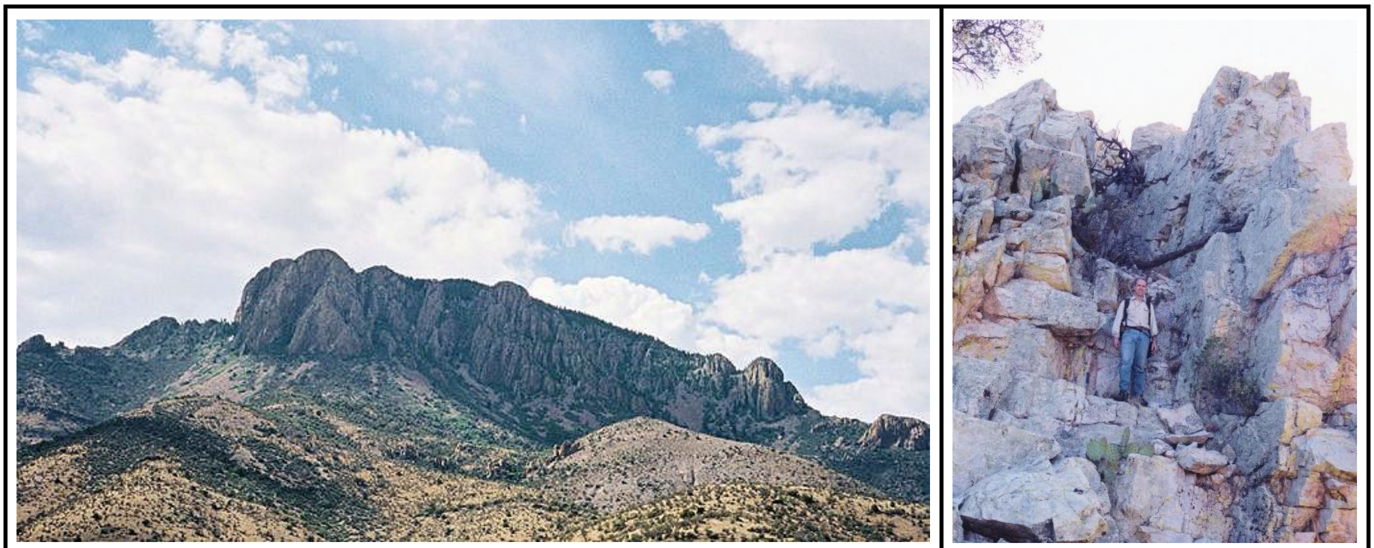


Figure C9. Indian Mountain capped with alunite-quartz rock, New Mexico, United States.
Right photo is a closeup of rock in capping.

Question C5-3 [10 marks]: Indian Mountain.

Referring to Figure C9, mark the following statements as true (**T**) or false (**F**):

1. The ridge represents a caldera. _________
2. The ridge represents the lithocap part of an epithermal model. ______
3. The deposit type represented might be a high-level expression of an underlying porphyry deposit. _____
4. The deposit type represented is a low-sulfidation epithermal deposit. _____
5. The deposit type represented is a high-sulfidation epithermal deposit. _____
6. The ridge marks a boiling zone. _________
7. The alunite-quartz rock is soft. _______
8. The water table was originally approximately at the top of the ridge. _____
9. The water table was originally somewhere near or below the base of the ridge. _____
10. The ridge marks a maar. _____

Figure C10. Feature is from the open pit at McLaughlin, northwestern California, United States.

Question C5-4 [10 marks]: McLaughlin, northwestern California, United States.

Referring to Figure C10, mark the following statements as true (**T**) or false (**F**):

1. The textures below the lens cap are called 'button textures'. ______
2. The textures below the lens cap are called 'geyser eggs'. ______
3. The texture implies surficial boiling. _______
4. The features are called accretionary lapilli formed as mud-hailstones from volcanic eruptions. _____
5. These are silica-replaced plant stems. _______
6. These textures imply a hot-spring environment of formation. _____
7. This texture implies that the rock is part of the lithocap. _______
8. This texture implies that the rock is hypogene. _______
9. The texture might develop in boiling mudpots. _____
10. These textures are very common in lithocaps. ______

Figure C11. Rock from a surface outcrop at Goldfield, southwestern Nevada, United States.
Goldfield is GL in Figure 91.

Question C5-5 [15 marks]: Goldfield, southwestern Nevada, United States.

Based on Figure C11, mark the following statements as either true (**T**) or false (**F**):

1. The rock represents hypogene mineralization. _____
2. The rock represents lithocap mineralization. _____
3. The rock has been leached by extremely acid fluids. ______
4. The rock is almost all feldspar. ______
5. The rock is almost all quartz. _____
6. The rock indicates that possible related deposits are low-sulfidation type. ______
7. The rock indicates that possible related deposits are high-sulfidation type. ______
8. Generally stable aluminum has been removed from the original rock. ______
9. The vugs in the rock are lined by late quartz. _______
10. The vugs represent boxwork after original sulfides. ______
11. This rock will fizz with dilute HCl. ______
12. This rock type can be generated by surficial, supergene weathering of a pyrite-rich original rock. _____
13. The vugs in the rock result from volume shrinkage of original rock volume. ______
14. Gold is never associated with this type of rock. ______
15. This type of rock always fluoresces under short-wave infrared light. _____

Figure C12. Outcrop at Goldfield, central Nevada, United States.
The Goldfield deposit is GF in Figure 91.

Question C5-6 [5 marks]: Goldfield., central Nevada, United States.

Based on Figure C12, mark the following statements as either true (**T**) or false (**F**):

1. The outcrop is yellow from limonite. _______
2. The outcrop is yellow from native sulfur. ______
3. The outcrop represents supergene alteration. ______
4. The outcrop represents steam-heated lithocap. _____
5. The yellow mineral is a secondary antimony mineral. _____

Figure C13. Outcrop from Goldfield, southwestern Nevada, United States.

Question C5-7 [5 marks]: Goldfield.

Based on Figure C13, the white rim on the vein is called (mark the following statements as either true [**T**] or false [**F**]):

1. A vein ___
2. Pervasive silicification ___
3. An envelope ___
4. A halo ___
5. A selvage ___

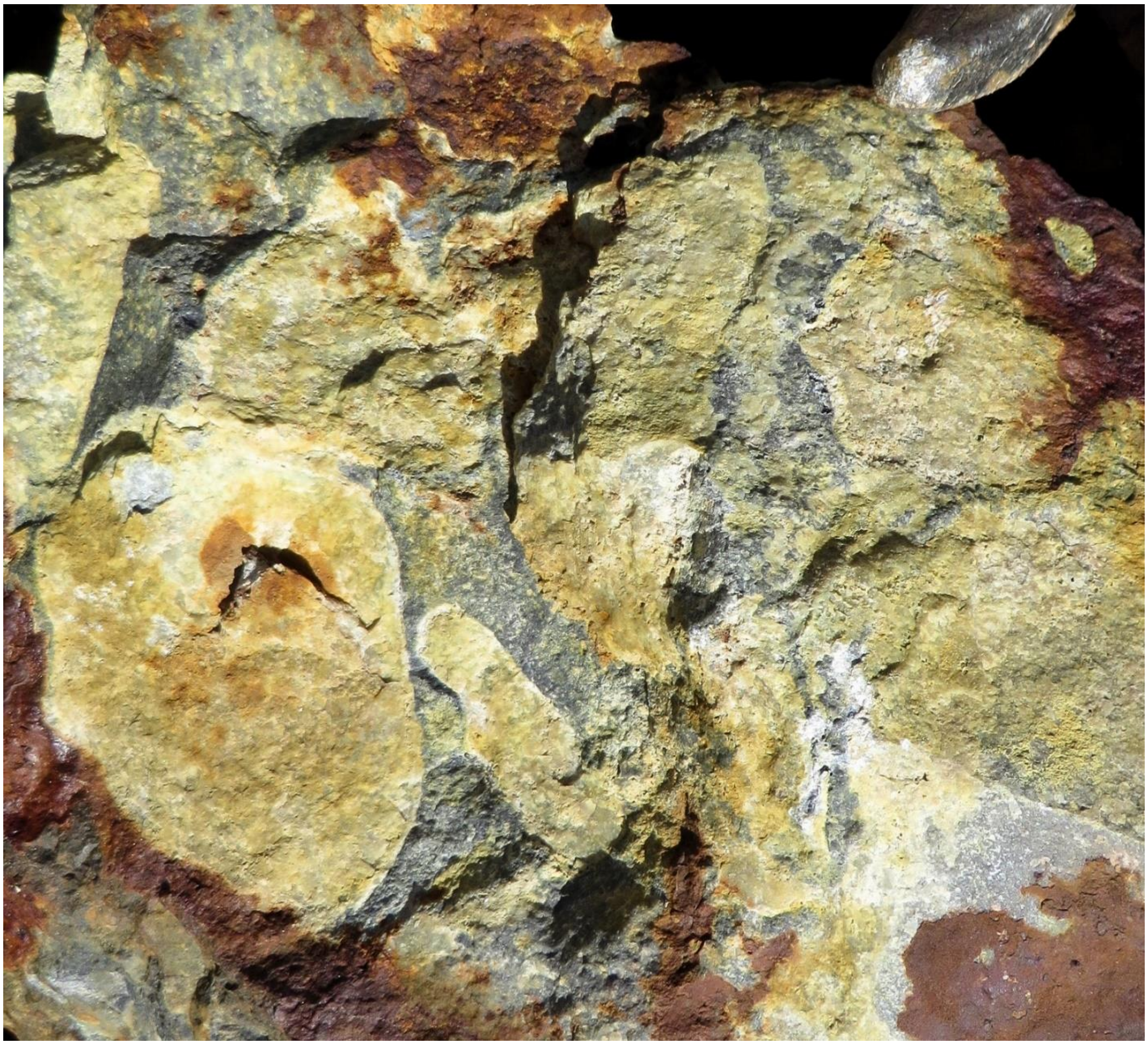


Figure C14. Important habit.
Tip of prospector's pick, upper right, provides scale. Photo was taken by John Bradford.

Question C5-8 [10 marks]:

Mark as true [**T**] or false [**F**] the following descriptions of the rock in Figure C14:

1. The rock is a breccia. ___
2. The rock is a porphyry. ___
3. The habit is gusano. ___
4. A microvein cuts the specimen. ___
5. The blobs likely contain pyrophyllite. ___
6. The blobs likely contain alunite. ___
7. The blobs likely contain quartz. ___
8. The habit is an index fossil for underlying porphyry deposits. ___
9. This habit occurs in a lithocap. ___
10. These are fossil worm tracks in siltstone. ___

Mark Summary for Questions C1 to C5

Record and summarize your marks in TABLE C2, below.

TABLE C2. Mark summary.

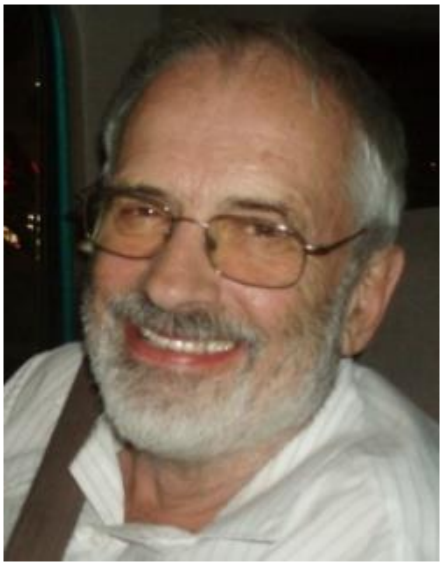
TOPIC/QUESTION NUMBER	MAXIMUM	MARK OBTAINED
C1: Regional Geology		
C1-1	6	
C2: Mineralogy		
C2-1	10	
C2-2	110	
C2-3	25	
C2-4	10	
C3: Rock Types		
C3-1	6	
C3-2	6	
C3-3	5	
C3-4	5	
C3-5	5	
C3-6	5	
C4: Structure and Tonnages		
C4-1	2	
C4-2	5	
C5: Textures		

C5-1	10	
C5-2	5	
C5-3	10	
C5-4	10	
C5-5	15	
C5-6	5	
C5-7	5	
C5-8	10	
Totals: Section Totals C1 to C5	**270**	

Your mark.

Calculate your percentage from: [(your total mark) / 270] × 100 = (your percentage correct).

Your mark = _____ %.



ABOUT THE AUTHOR

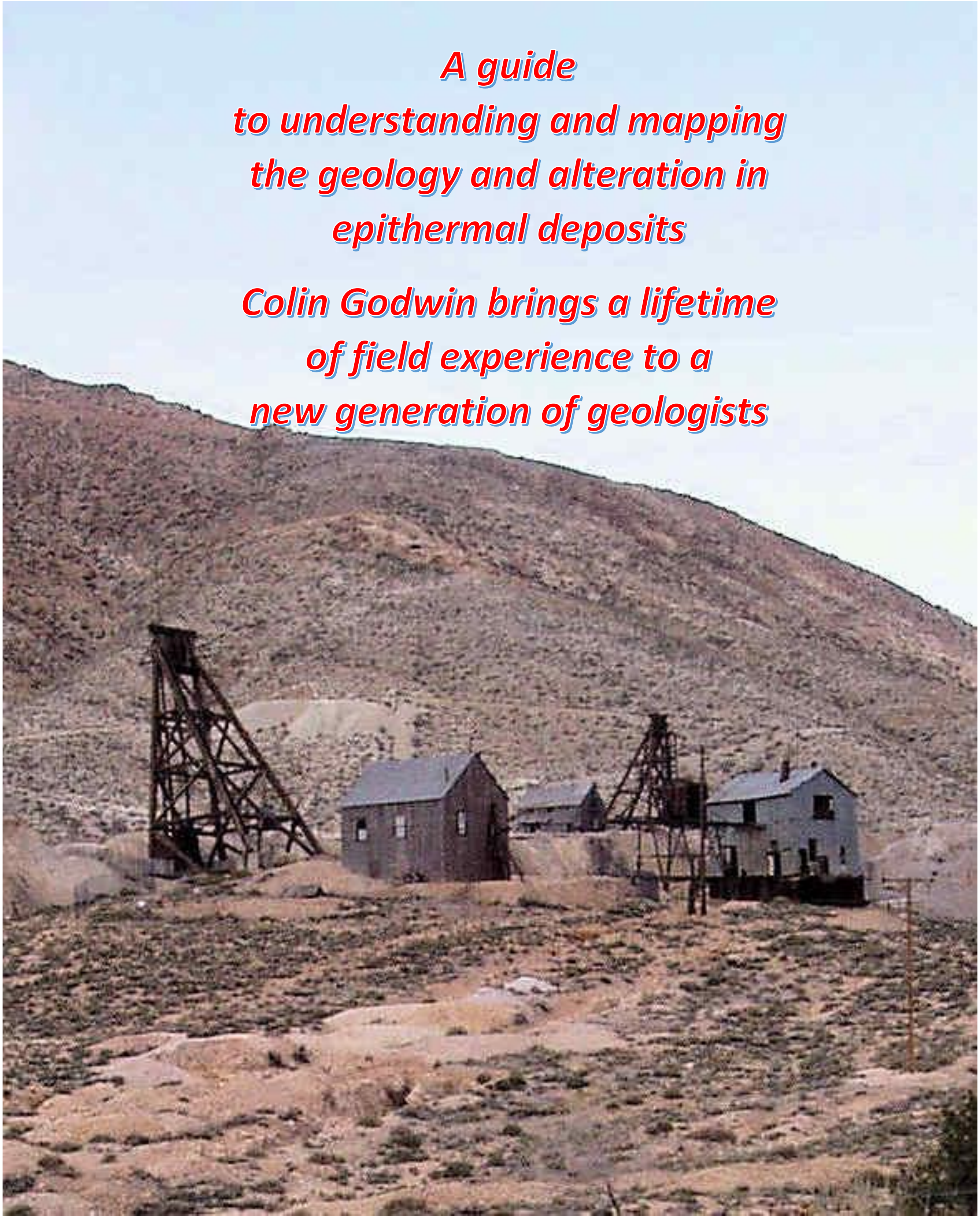
Dr. Colin I. Godwin (BASc [UBC], PhD [UBC], PEng [BC], PGeo [BC]) taught the exploration for, and the geology of, mineral deposits at The University of British Columbia (UBC) from 1975 to early retirement in December 1999. During part of that time, he was Director of Geological Engineering. He is now a Professor Emeritus of UBC's Department of Earth, Ocean, and Atmospheric Sciences. While at the university he collaborated with students specializing in field and laboratory studies of most types of deposits, including porphyry, skarn, epithermal, volcanogenic, and kimberlitic deposits. Interpretation of lead isotopes in galena, as related to mineral exploration, was one of his academic focuses. Colin received the Duncan R. Derry Medal from the Mineral Deposits Division of the Geological Association of Canada in 1990.

Colin was a founding director of International Geosystems Ltd. in the early 1970s when he became involved in the development of the Geolog® System while studying the Casino copper-gold-molybdenum porphyry deposit in the Yukon for his Doctorate. Geolog was one of the first computer-based schemes for the comprehensive capture and interpretation of data from exploration and development work, especially drillholes. He has worked on exploration programs in Australia, Canada, United States, Mexico, Central America, and South America.

He can be reached at: 2706 – 660 Nootka Way, Port Moody, BC, Canada V3H 0B7. Tel: (604)939-6507. Cell: (778) 989-6507. Email: cigodwin@gmail.com. Should copies of logging formats or answers to the questions be required contact Colin.

This guide provides the basis for identification and description of key features and models for epithermal deposits that includes related geology, ore mineralization, alteration mineralization and ore location. It is an important guide for exploration geologists.

Back cover is a photo taken in 2003 of old workings in the Tonopah epithermal silver camp, Nevada, United States.


A guide
to understanding and mapping
the geology and alteration in
epithermal deposits
Colin Godwin brings a lifetime
of field experience to a
new generation of geologists