Ore Deposits #10. A Canadian Cordilleran Model for Epithermal Gold-Silver Deposits

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Introduction

Discovery of lode gold in 1851 and placer gold in 1857 initiated the first large-scale economic activity in British Columbia and led to a major influx of miners during the gold rushes of the mid- and late 1800's. This explosion of non-native population necessitated colonial expansion, the creation of new settlements, developments of infrastructure, and provided the economic base for the fledgling colony.

Total gold production to date from the Canadian Cordillera (British Columbia and Yukon) is close to 1,182 tonnes (38 million ounces), approximately one-third of the amount produced by Ontario. About 60% of Cordilleran gold comes from lode deposits; the remainder has been won from placer workings. Placer gold production peaked in 1900; lode gold production peaked in 1939 when 18.3 tonnes of gold were produced in British Columbia. Thereafter, output declined steadily until the early 1970's when by-product gold, mainly from porphyry copper mines as well as massive sulphide and skarn deposits, became the dominant source. These accounted for up to 80% of the annual 3-4 tonnes of gold production.

Gold was liberated in international markets in 1968 from the fixed price of $35US per ounce set in 1934. The resulting price increases, culminating in spectacular price peaks in late 1979, renewed interest in known deposits and enlivened the quest for new supplies of both gold and silver. The search for gold has been the main focus during the 1980's of the mining exploration community, a $100 million annual enterprise in the Canadian Cordillera. One of the primary targets has been gold-silver deposits of the "epithermal type", also known variously as "bonanza ores", "Tertiary type", "precious metal deposits of volcanic association" or "fossil hot spring type" (Figure 1 and Table 1).

Epithermal precious metal deposits are attractive, especially when base metal prices are depressed, because they have high unit values of precious metals with generally low or no base metal content. The deposits commonly occur as small vein systems (less than a million tonnes in size) but they tend to have good grades, and many contain high-grade ore shoots. They provide quick payback at high rates of return on modest amounts of invested capital. Consequently, epithermal

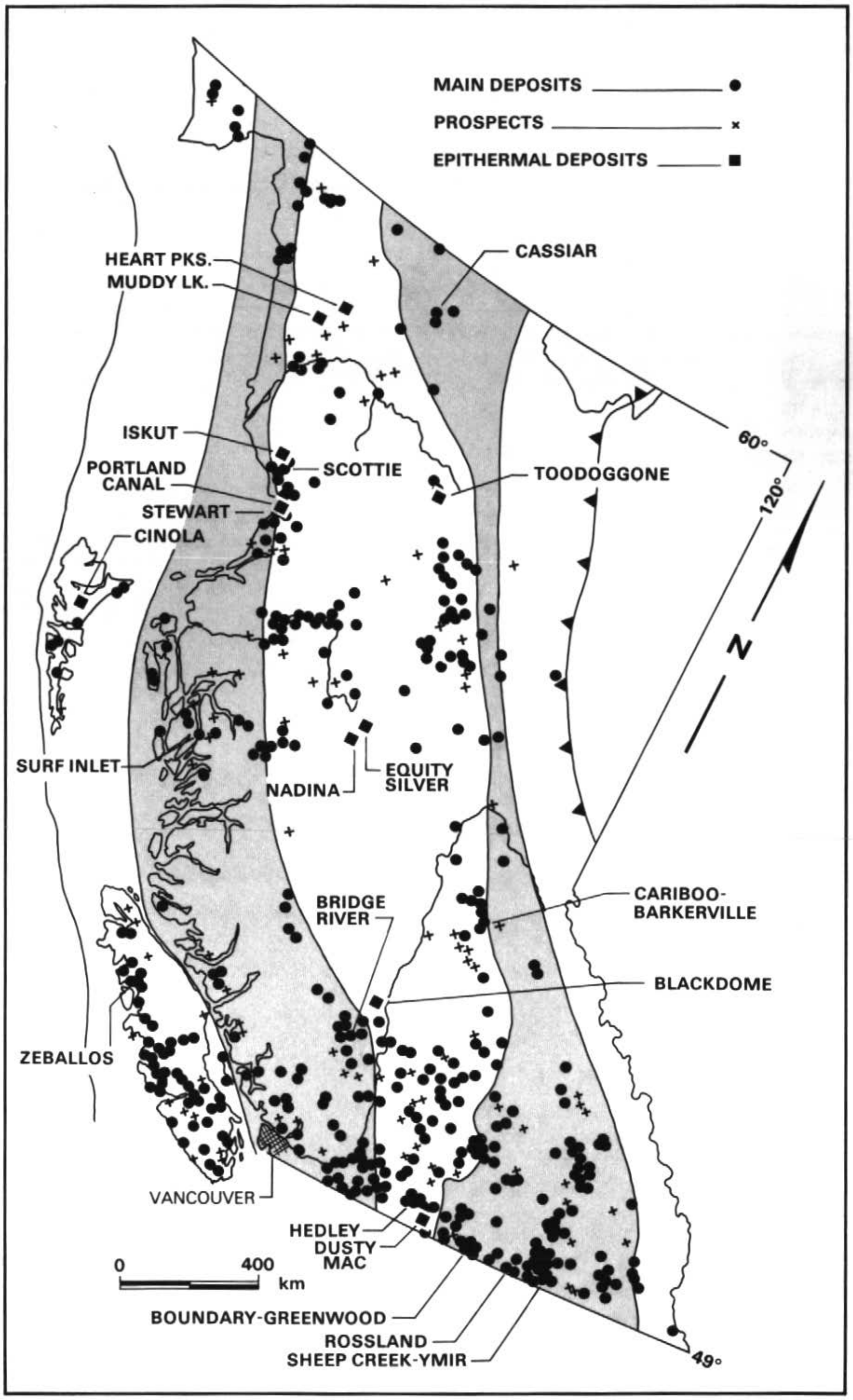

Figure 1 *Distribution of gold deposits in British Columbia showing major camps, individual deposits and areas of recent exploration activity. Lines indicate major tectono-physiographic boundaries. Crystalline-metamorphic terranes of the Coast Plutonic Belt in the west and Omineca Belt in the east are shown by the hachured pattern.*

deposits are particularly attractive to smaller companies that seek financing primarily from public sources. In addition, major mining companies, with long-term investment strategies and the ability to support major capital outlays, seek larger epithermal prospects suitable for open-pit operations. An example of the type of superior epithermal deposit that explorationists strive to find is the El Indio Mine, Chile, which began limited production in 1979. In its first year of operation, 12,800 kilograms of gold were produced from 50,000 tonnes of direct shipping ore. There remained 70,000 tonnes of similar material containing 277 grams gold per tonne as well as main reserves of 3.2 million tonnes with 12.3 grams gold per tonne, 141 grams silver per tonne, and 4.0% copper (Walthier *et al.*, 1982).

Characteristics of Epithermal Deposits

The term "epithermal" was introduced by Waldemar Lindgren in 1933. It is part of a genetic classification of ore deposits that describes hydrothermal fluid sources and depth zones in such terms as "epithermal", "mesothermal", and "hypothermal". Epithermal deposits were considered (Lindgren, 1933, p. 212) to be formed "by hot ascending waters of uncertain origin, but charged with igneous emanations. Deposition and concentration (of ore minerals occurs) at slight depth". He considered temperatures to range from 50-200°C under conditions of "moderate" pressure. Lindgren also noted that epithermal deposits have "striking analogies to those products of the hot springs". Other workers, such as Buddington (1935), recognized that temperatures greater than those suggested by Lindgren were possible in near surface hydrothermal environments. Soon the upper temperature limit for epithermal deposits was extended to at least 300°C. Use of the term "epithermal" became well entrenched in North America and elsewhere during the 1940's and 1950's. Many descriptions of epithermal-type deposits and districts accumulated and document the geometry, structural controls, and mineralogical variations of these deposits.

Review articles describing "epithermal" deposits abound; each period of renewed interest in gold produced updated summaries. Notable descriptions include: Schmitt (1950a), Wisser (1966), Sillitoe (1977), Berger (1982), Berger and Eimon (1982), Silberman (1982), and Heald-Wetlaufer *et al.* (1983). They emphasize the following characteristics:

(1) The deposits form near the surface. Mineralization takes place from surface to a maximum depth of about 1,000 metres. Ore can be developed over a considerable strike length but is restricted in vertical extent to intervals varying from 100 to 1,000 metres. Average vertical range of ore is about 350 metres; it rarely exceeds 600 metres. Ore zones (ore shoots) bottom in either barren rock or pass downward into sub-economic zones containing base metal sulphides.

(2) Veins are the most common ore host; they tend to branch or flare upward into complicated, wedge-like or cone-like features. Breccia zones, stockworks, and fine-grained bedding replacement zones also occur; larger zones of these types may extend to tens of millions of tonnes in size.

(3) Deposits form in extensional tectonic settings, in areas with well-developed tension fracture systems and normal faults. The fracture systems are commonly, but not necessarily, associated with large-scale volcanic collapse structures.

(4) Mineralization commonly occurs in volcanic terranes with well-differentiated, subaerial pyroclastic rocks, and numerous small subvolcanic intrusions. Hot spring deposits and fumarolic volcanic phenomena are sometimes evident where centres of hydrothermal discharge have not been deeply eroded.

(5) Ore and associated minerals are deposited dominantly as open space filling with banded, crustiform, vuggy, drusy, colloform, and cockscomb textures. Repeated cycles of mineral deposition are evident. Ore minerals are generally fine-grained but commonly have coarse-grained, well-crystallized overgrowths of gangue minerals. Some replacement textures are evident; pseudomorphs of quartz after calcite are characteristic. (See Figure 2).

(6) Gold and silver are the main economic metals, and occur along with enhanced amounts of Hg, As, Sb and rarely Tl, Se, and Te. Gold to silver ratios range widely; silver is typically more abundant than gold. Main ore minerals are native gold and silver, electrum, acanthite (argentite), and silver-bearing arsenic-antimony sulphosalts. Tellurides are locally important. In addition, galena and sphalerite are common; copper occurs generally as chalcopyrite but in some deposits forms enargite. Cinnabar, stibnite, tetrahedrite, and selenides are important in some deposits.

(7) Gangue minerals are mainly quartz and calcite with lesser fluorite, barite, and pyrite. Chlorite, hematite, dolomite, rhodonite, and rhodochrosite are less common. Silica occurs in many varieties, most commonly as quartz or amethystine quartz, but also as opal, chalcedony, and cristobalite.

(8) Hydrothermal alteration is pronounced. Precious metal mineralization is frequently associated with silicification. Zones of silicification can be flanked by zones of illite-sericite and clay alteration, all occurring within larger zones of propylitic alteration. At depth, vein structures contain adularia; near the surface, broad argillic zones, some containing alunite, can predominate. Some deposits have aluminous, advanced argillic alteration assemblages containing: kaolinite/dickite, sericite, pyrophyllite, and andalusite with accessory diaspore, corundum, topaz, zunyite, lazulite or scorzalite, dumortierite, and rutile or anatase.

Table 1 Reserves and Production, British Columbia Epithermal Deposits

Deposit	Production (million tonnes)		Au (kg)	Ag (kg)	Reserves
Silbak Premier	1918-1976	4.2	56,000	1,271,000	~4 mt, 2.43 g/t Au, 110.4 g/t Ag
Equity Silver (Sam Goosly)	1980-present	~7	3,300	696,000	~21 mt, 0.35% Cu, 0.85 g/t Au, 109 g/t Ag
Big Missouri	1927-1942	0.8	1,800	1,600	~2 mt, 3.36 g/t gold-equivalent
Baker (Chappelle)	1980-1983	0.08	1,200	23,000	–
Dusty Mac	1969-1976	0.06	600	10,500	–
Nadina	1972-1973	0.2	<10	13,700	577,600 t, 3.1 g/t Ag, 213 g/t Ag, some Pb, Zn, Cu
Cinola					~34 mt, 2.06 g/t Au
Lawyers	–				>1 mt, 7.27 g/t Au, 254.2 g/t Ag
Blackdome	–				195,000 t, 27 g/t Au, 110 g/t Ag
Mt. Johnny (Iskut R. area)	–				554,000 t, 21.3 g/t Au, some Ag, Pb, Zn, Cu

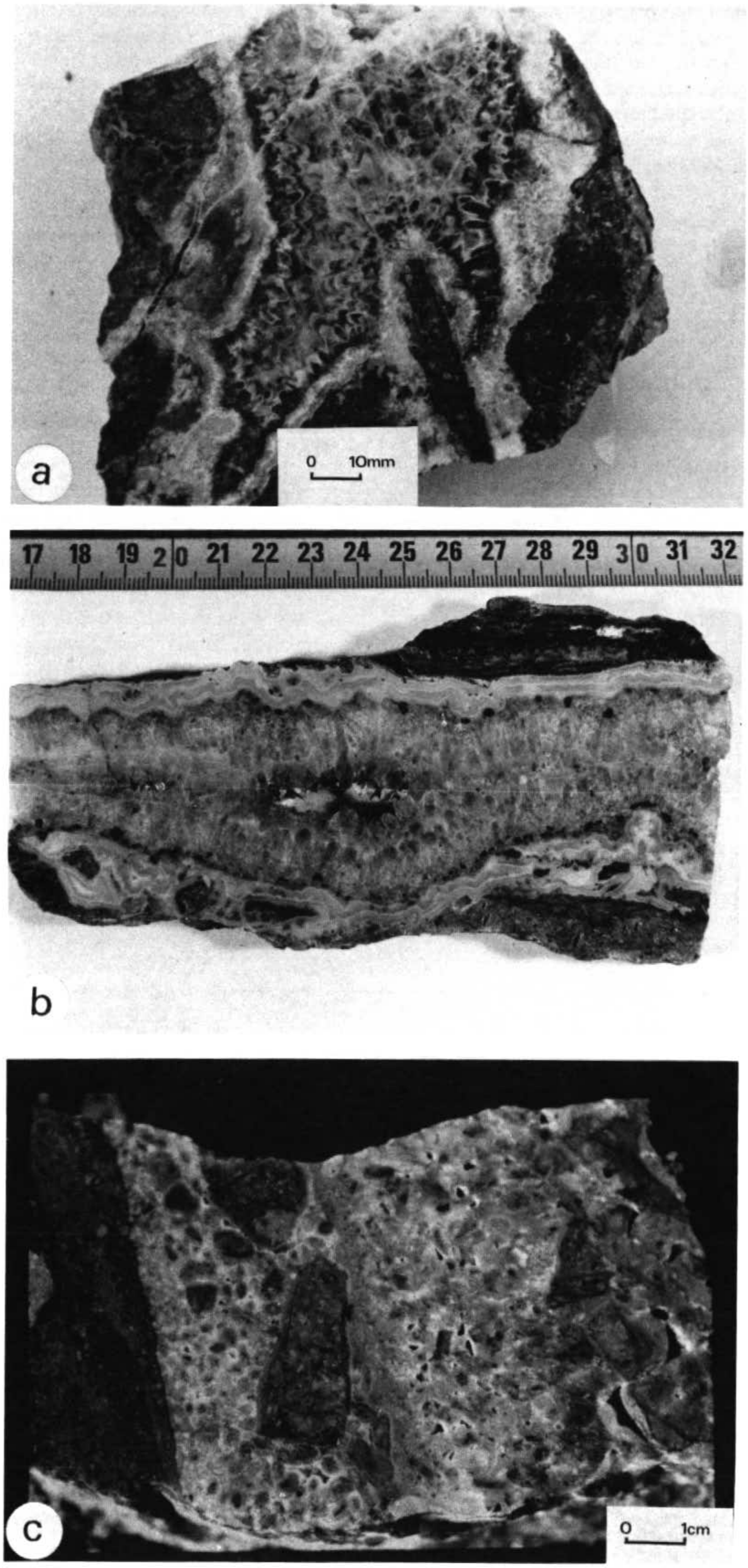

Figure 2 *Textures of epithermal ores: (**a**) crystalline amethystine quartz in an irregular vein. Fine-grained quartz marks the vein margin and there is an adularia selvage at the wall rock contact, Lawyers deposit, Toodoggone area, British Columbia; (**b**) banded chalcedonic quartz forms the vein walls; crystals of galena and sphalerite (dark grains), and fine-grained fluorite occur at the contact with inner zone amethystine quartz, Creede, Colorado; (**c**) vuggy breccia with fragments rimmed by chalcedonic quartz and fine-grained crystalline quartz overgrowths, Lawyers deposit, Toodoggone area, British Columbia.*

Genesis of Epithermal Deposits

Studies of recent and active geothermal systems, such as those by Henley and Ellis (1983), Weissberg (1969), Weissberg *et al.* (1979), Ewers and Keays (1977), and White (1981), have done much to demonstrate the relationship between hot springs and epithermal deposits, a relationship noted by Schmitt (1950b) and strongly promoted by White as early as 1955. The concept that ascending magmatic-source hydrothermal fluids are important has been largely eliminated, mainly by fluid inclusion and stable isotope studies. Epithermal deposits are now considered to form from relatively dilute, near-neutral to weakly-alkaline chloride waters (<5 weight per cent (wt.%) NaCl equivalent) that undergo boiling or effervescent degassing, fluid mixing, and oxidation at temperatures generally between 200-300°C, and most commonly between 230-260°C. Boiling or mixing of fluids as they ascend or migrate laterally appear to be the two most important cooling mechanisms. Downward migration of fluids has been documented in one locality, Creede, Colorado, where hydrothermal fluids in at least part of the hydrothermal system have mixed with denser, cooler brines (Bethke and Rye, 1979).

Recent detailed studies of a number of Tertiary epithermal deposits in caldera settings, principally by geologists from the United States Geological Survey, thoroughly document the geologic settings and present perceptive, well-researched explanations of the origins of these deposits (Steven and Eaton, 1975; Lipman and Steven, 1976; Lipman *et al.*, 1976; Casadevall and Ohmoto, 1977; Slack, 1980; and others). The authoritative descriptions and genetic interpretations of these deposits has led to extensive comparisons with other deposits and areas. Unfortunately, many new workers and explorationists place undue emphasis on the caldera or resurgent caldera setting of the deposits. Consequently, there is a widely-held notion that calderas are a requisite for the development of epithermal deposits. This is not the case. In fact, calderas, as described by Smith and Bailey (1968), are simply a type of very specialized volcano, they do not inherently contain any mineralization. In Nevada, only 2 out of 31 recognized calderas are known to contain ore (McKee, 1979), and in the western United States, only 14 out of 125 known calderas have any associated ore (Rytuba, 1981). If ore occurs, it is because calderas produce large fracture systems, but any major fracture system that channels hydrothermal fluids can localize mineralization.

Radiometric data from epithermal deposits in Tertiary volcanic areas of the southwestern United States (Silberman and McKee, 1974; and others) show that ores are 2-17 million years younger than the caldera-forming volcanism. Thus it seems that hydrothermal activity is not genetically related to caldera volcanism, but is related to younger, subvolcanic magmatic activity in structurally disturbed rocks at the caldera margins and in the surrounding rocks.

Association of epithermal ores with felsic volcanic rocks (rhyolite and dacite flows, domes, ash flow sheets, and tuffs) has also been overemphasized. Epithermal ores occur in all rock types, particularly those that sustain large, open-fracture systems over extended periods of time during hydrothermal activity. In Nevada, McKee (1979) noted that in 98 mining districts with economically significant ore production, only 5 districts were in siliceous tuffs; the majority of mineral deposits were in andesitic hypabyssal and extrusive volcanic rocks. Andesitic pyroclastic rocks or flow breccias appear to preferentially maintain zones of primary high permeability during hydrothermal activity. In addition, andesites can sustain fault and fracture-related dilatent structures and openings, such as cymoid structures or cymoid loops, over long periods of mineralization.

In summary, hydrothermal activity is only rarely related to caldera development or resurgence but the ore-controlling structures may be. The heat for hydrothermal activity does not appear to be the latent heat of volcanism but is more likely derived from structurally controlled subvolcanic intrusions or deeper plutons. Any rock type that maintains primary or structurally induced permeability and permits focussed hydrothermal fluid flow can provide sites for ore deposition.

Zoning of Hydrothermal Alteration — The Key Exploration Guide

Passage of hydrothermal fluids through fractured rocks produces structurally controlled zones of hydrothermal alteration. In most epithermal districts at least some hydrothermal alteration is evident as readily visible zones of bleached rock. Larger alteration zones can be many kilometres in dimension; the ore zones are a few metres or tens of metres, at best. The challenge to the explorationist is to properly assess the alteration zones for economic potential and to locate and define structural features that provided a focus for sustained hydrothermal fluid flow.

Propylitic alteration (chlorite, calcite, pyrite, epidote, zeolite) is an early-developed, widespread and district-wide alteration in many epithermal districts. The term "propylite" was introduced by von Richthofen in the late 1800's to describe distinctive rocks in the famous Comstock Lode epithermal camp, Virginia City, Nevada. Within the broad areas of propylitic alteration are more restricted zones of sericitic alteration or recessive weathering clay alteration (illite-kaolinite-montmorillonite). These surround central zones of silicification or quartz veining, some portions of which may be mineralized. The silicified zones are more resistant and commonly form local heights of land, many of which in old mining areas are sites of mine headframes or other workings.

The Buchanan "Boiling" Model. Buchanan (1981) summarized and tabulated data for many of the western US epithermal deposits and presented a model, now widely circulated and utilized by explorationists in the Cordillera, that effectively illustrates the geometric arrangement of ore and alteration zones in "typical" epithermal veins that are hosted by volcanic rocks (Figure 3). The model describes a zone of mineralization that occurs along a dominant subvertical fracture system from a depth of about 500 metres to the surface; close to surface it splits into a series of subsidiary structures. The centre of ore deposition, placed by Buchanan at a depth of about 350 metres, has a discrete top and bottom. Above the ore zone, quartz veining persists but diminishes progressively in abundance upward, as do precious and base metal amounts. Similarly, quartz becomes progressively finer-grained upward and becomes opaline silica or chalcedony in the upper part of the zone. If the silica-rich hydrothermal fluids discharge at surface as hot springs, mushroom-shaped caps of siliceous sinter are deposited. Alternatively, in veins with less dynamic fluid flow regimes, surface expressions of deeper hydrothermal activity may be nothing more than thin calcite veins or clay-altered zones in wall rocks adjoining faults or fractures. At the base of the ore zone, Buchanan describes two types of ore terminations. In one type, quantities of ore diminish downward and quartz veins that continue to depth are barren or contain only minor chalcopyrite and pyrrhotite. In the second more common type, precious metals, galena, and sphalerite occur in sub-economic amounts at depth together with minor pyrite and chalcopyrite. In both cases, calcite and adularia contents decrease with depth.

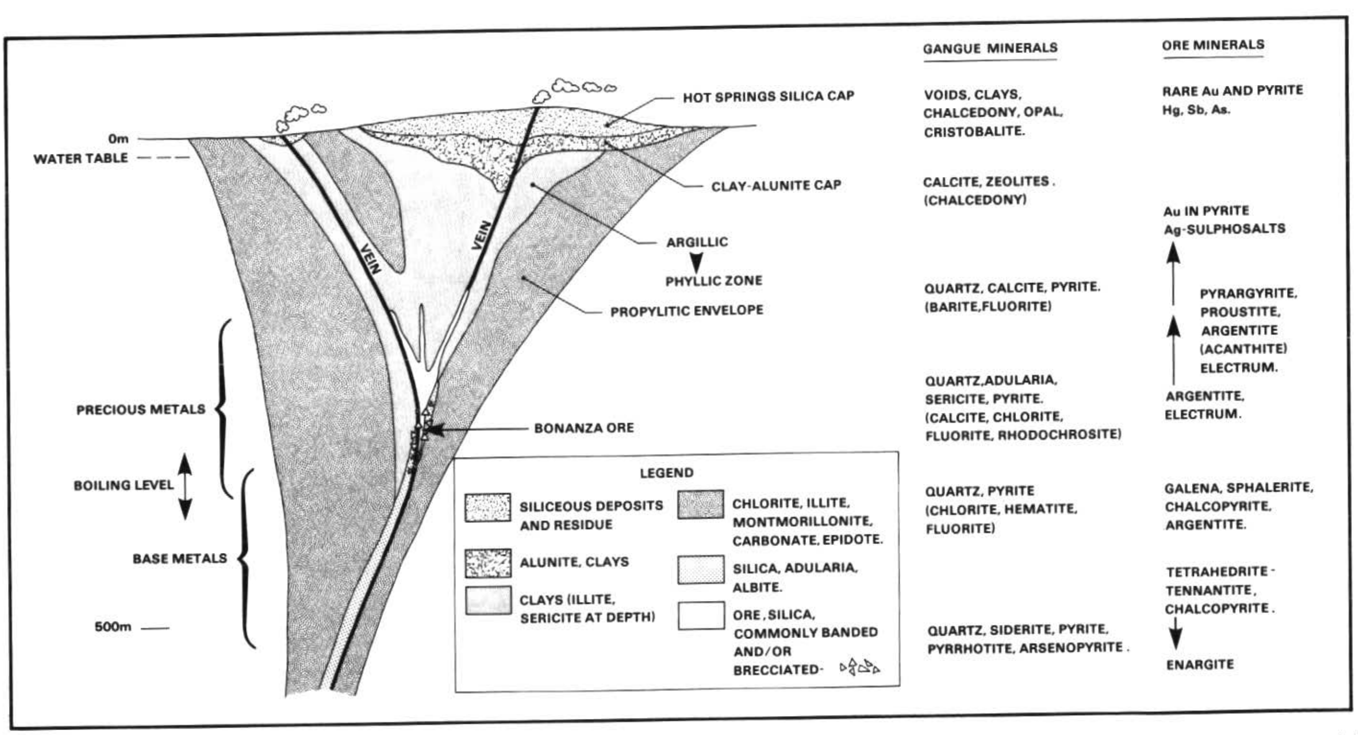

Figure 3 *Idealized section of a bonanza epithermal deposit, after Buchanan (1981). Real systems are commonly more complex because this single stage model is overprinted by several stages of mineralization related to migration of fluid boiling or degassing levels.*

Buchanan (1981) concluded that ore deposition and attendant wall rock alteration resulted from boiling and oxidation of the ascending hydrothermal fluids. In the model, repeated self-sealing is followed by episodic refracturing and brecciation along the ore structures. The attendant pressure drops cause boiling that results in mineral precipitation. This produces multiple stages of ore deposition, and the distinctive, layered and symmetrically-banded ore textures so common in epithermal deposits. The boiling level is controlled by the temperature and salinity of the fluids; hydrostatic fluid pressures are considered to prevail in this type of shallow, open-fracture system. Boiling causes a decrease in fluid temperatures and vapour loss that increases pH in the ore fluids. At the start of boiling, after a slight loss of volatiles, solutions become neutral to slightly alkaline; with a 20% vapour loss and more alkaline conditions, silver minerals deposit along with adularia, minor sericite, and abundant silica. At the top of the boiling zone, vigorous boiling leads to faster vapour loss with attendant rapid cooling. At higher structural levels, the released vapours may condense into oxidized, acidic fluids. In this environment the various gold complexes (bisulphate, chloride, thiocomplexes, or others) destabilize and gold precipitates along with copious amounts of silica (Seward, 1973). At or near surface, any remaining volatiles that are released condense to form a highly-oxidized, acidic environment. The strong acid solutions formed can be diluted by the neutral groundwaters but are generally only weakly chemically buffered. Extensive and intense sericitic or argillic alteration develops in this zone. This so-called "low pH or acid capping" characterizes many epithermal deposits. The clay alteration zones are generally not of ore grade but commonly have anomalous amounts of Au, As, Pb and less commonly Hg, Sb, W, Mo, B and Ag; some contain alunite ($KAl_3(SO_4)_2(OH)_6$). The size of sericite-clay zones tends to be proportional to that of related orebodies — the larger the alteration zone, the larger the zone of mineralization.

Buchanan's model is frequently criticized. Despite many detailed studies of epithermal deposits and despite theoretical studies (Drummond and Ohmoto, 1985), only a few deposits show evidence of boiling. In fluid inclusions boiling is indicated by widespread entrapment of various amounts of vapour in ore and gangue minerals, and the presence of remnant concentrated brine. An alternative explanation, based on the dilute nature of fluids in epithermal deposits and the isotopic signatures of vein minerals (O'Neil and Silberman, 1974; Radtke *et al.*, 1980), is that the hydrothermal systems are free-flowing fluids derived from, and recharged by, meteoric waters that undergo little isotopic exchange with wall rocks. Models that postulate mixing of fluids as a cooling and oxidizing mechanism have been discussed by Henley and McNabb (1978), Henley and Ellis (1983), Hedenquist and Henley (1985), and others. In their models developed from studies of active geothermal fields, hydrothermal fluids, which are primarily deeply-circulating meteoric waters, are heated, rise in a buoyant thermal plume, and then mix with cooler, oxygenated, neutral to acidic surface waters.

Buchanan's major contribution is his clear description of ore and alteration mineral zoning and the spatial relationship between mineralizing solutions and the paleosurface. Undoubtedly most ore fluids have complex histories, some including both boiling (Drummond and Ohmoto, 1985) and fluid mixing (Casadevall and Ohmoto, 1977). Uncertainty about the mechanism of ore deposition in epithermal systems does not lessen the usefulness of Buchanan's empirical model. Once the position of the paleosurface has been recognized or postulated from geological field data, the model provides a useful guide for estimating depths to mineralization.

A Hot Spring Model — Acid-Sulphate Siliceous Alteration. White (1955) described a number of active springs with associated epithermal mercury and gold-silver deposits. In 1981 he stated: "The correlation of fossil geothermal systems (ore deposits) with present-day active systems provides insights into possible origins of various constituents of ore-generating systems". One of the best-studied examples is at Steamboat Springs, near Reno, Nevada, where active hot springs and areas of steaming ground have been extensively studied and nearby mineral deposits genetically related to extinct hot springs have been exposed by shallow pits and tested to depth by boreholes.

Modern siliceous hot spring deposits and their partially-exposed underlying altered rocks represent the "silica cap" and "low pH acid cap" described by Buchanan (1981) as the surface products of an epithermal system. The siliceous sinter deposited is porous at surface but compacted and cemented at depth; it consists of opaline silica, chalcedony, and cristobalite. The deposits at Steamboat Springs were formed by hot springs related to underlying, 1-3 million year old rhyolite domes. Maximum water temperature measured in boreholes is 186°C. The sinters are enriched in Au, Ag, Sb, Hg, As, Tl and B (White, 1981); locally, black, siliceous muds contain crystalline stibnite, or metastibnite, and cinnabar. Uphill from the active hot springs, fossil ponds are now seen as small lenses of chalcedony, some of which contain up to 0.1% Hg in the form of cinnabar or metacinnabar.

Altered rocks underlying the hot spring deposits, which were originally basaltic andesite and granodiorite, are now exposed in the nearby "Silica Pit" as zones of bleached, white clay-alunite-silica rock. The alteration is caused by sulphuric acid fumes that still issue from fractures in the walls and floor of the pit. The vapours deposited enough sulphur and mercury to permit recovery of crystalline native sulphur and earthy cinnabar from another, nearby excavation. Visible cinnabar is restricted to a zone within 15 metres of the present ground surface, and analytical detection of mercury is possible to 26 metres (White, 1981). Stibnite along with arsenic values are found somewhat deeper, to a maximum depth of 46 metres. Values of up to 15 ppm gold, 150 ppm Ag, 3.9% Sb, and 0.1% Hg are obtained from siliceous muds in the sinter; native sulphur and possibly some cinnabar are deposited above the groundwater table as sublimates from vapours. The position of the groundwater table marks the boundary between hot waters and the vapour-dominanted fluids (White *et al.*, 1971). Above this boundary, where H_2S is oxidized to H_2SO_4 and condenses to aqueous sulphuric acid, descending refluxing solutions cause the most severe acid-leaching. Schoen *et al.* (1974) have shown that the acid capping (solfateric alteration) at Steamboat Springs consists of the following zones from surface to depth: opal, cristobalite, and some anatase (presumably from the titanium-rich basaltic country rocks); opal, alunite, quartz, and minor pyrite; and kaolinite, alunite, montmorillonite and pyrite. Below the clay-alunite zone, narrow zones of montmorillonite and illite alteration are restricted to the walls of the hydrothermal channelways.

The Marysvale Replacement Model — Hydrothermal Alunite Deposits. Alunite-silica deposits associated with hydrothermal activity in volcanic areas can be large and distinctly zoned. In these deposits, central, silica-rich core zones or cappings are flanked and underlain by alunite-silica zones that pass laterally into argillic zones within broad areas of propylitic alteration (Figure 4). The deposits form bleached, locally iron-stained, resistant outcrops with rare native sulphur and cinnabar mineralization. They are of interest to exploration geologists because they indicate sulphur-rich hydrothermal activity and the potential for nearby or deeper precious metal deposits. The alunite-bearing hydrothermal systems represent another type of fossil hot spring deposit and constitute part of the low pH capping in Buchanan's model. Alunite mineralization forms deeper parts of the acid-sulphate alteration zones found at Steamboat Springs and other active hot springs.

Cunningham and co-workers (1984) derived a model for the replacement and vein alunite deposits (Figure 4) from long-term studies near Marysvale, Utah. Their model clearly describes the setting of the deposits, illustrates the alteration zoning, and explains their origins. At Marysvale, Miocene alunite deposits formed in lava flows, under highly oxidizing conditions, at the tops of convecting hydrothermal plumes spaced at three to four kilometre intervals around a central monzonite stock. A series of circular altered areas formed that are zoned laterally and vertically.

Central siliceous alunitic cores are surrounded by kaolinized rocks within a pyritic propylitic zone of regional extent. Vertical zoning produces a layered or "stacked" sequence in which a basal zone of alunite replacement is overlain, in sequence, by zones of silica-jarosite, silica-hematite, and a flooded silica capping. This mineralization apparently forms above the groundwater table, where ascending hydrothermal fluids "flash" into wet steam resulting in some condensation of vapours and a reflux of aqueous sulphuric acid into the system (Cunningham *et al.*, 1984). This type of alteration takes place above the water table at depths of generally less than 50 metres. This is a vital fact for explorationists because it establishes the position of the paleosurface, the most important datum plane in all depth-zoning models.

Cupriferous Pyritic Gold-Silver Deposit Model — Acid-Sulphate Aluminous Alteration. Arsenic and antimony-rich cupriferous pyritic gold-silver deposits referred to as the "hot and/or deep acid-sulphate type", form a distinctive group of mineral occurrences associated with acid-sulphate advanced argillic alteration (Knight, 1977). These deposits are characterized by aluminous alteration minerals, native sulphur, and abundant pyrite, enargite or other As, Sb minerals. Ashley (1982) classified them as enargite-gold deposits and Sillitoe (1983) described them as enargite-bearing massive sulphide deposits that form at high levels in porphyry copper systems.

The mineralization occurs over a wide vertical range, from shallow, near-surface volcanic environments with abundant breccia-related mineralization, to deeper, replacement deposits and porphyry copper stockwork systems in proximity to porphyritic intrusive rocks. Hydrothermal alteration is primarily argillic with abundant quartz, alunite, kaolinite, sericite-illite, and montmorillonite. Somewhat restricted advanced argillic zones contain the aluminous minerals pyrophyllite, kaolinite, and andalusite, as well as the related alteration minerals quartz, dumortierite, scorzalite, lazulite, corundum, zunyite, pyrite, hematite, topaz, and rutile (Wojdak and Sinclair, 1984). Advanced argillic alteration zones generally underlie or occur within the broader argillic alteration zones. Ore mineralization occurs within the advanced argillic zones but is more commonly present at the transition from argillic to advanced argillic aluminous alteration, as at Goldfield, Nevada (Ashley, 1974). Preliminary fluid inclusion data from Goldfield (Ashley, 1984) and the widespread presence of pyrophyllite and some diaspore, suggest that the advanced argillic aluminous alteration assemblages form above the hydrothermal stability limit of kaolinite at temperatures of at least 300°C. The ore minerals, which generally line or fill open spaces in breccia zones, formed later, probably as the hydrothermal systems cooled. Mineralized structures may contain abundant pyrite; zones with up to 15% or, more, pyrite are common. Local small massive sulphide lenses may also be present. Enargite-luzonite, tetrahedrite-tennantite, silver sulphosalts, and minor amounts of base metal sulphides are the main ore minerals; tellurides occur in some deposits.

The deposits originated from hot fluids emplaced at depths ranging from slight to far below any hot spring discharge sites. The

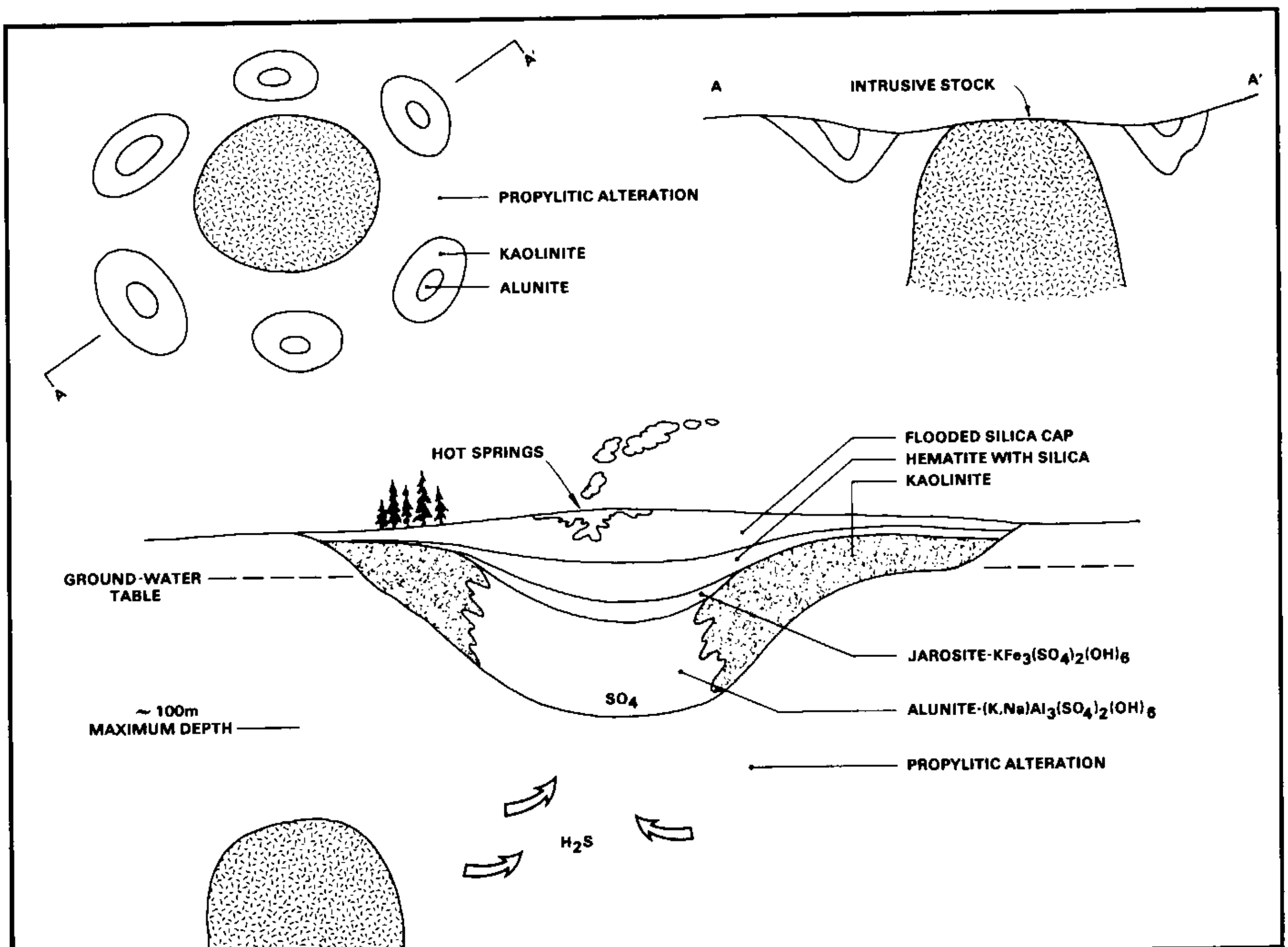

Figure 4 *Diagrammatic representation of the argillic-alunite alteration model described by Cunningham, Rye, Steven, and Mehnert (1984). A central intrusive body is surrounded by hydrothermal convection cells that cause zoned areas of alteration to form. Distinct vertical and some lateral mineral zoning in individual alteration zones (lower part of figure) is related both to near surface boiling and oxidation of fluids at the groundwater table.*

near surface deposits are, therefore, "telescoped", as defined by Spurr (1923, p. 292-308) in his book "The Ore Magmas". The definition implies that deposition took place at unusually high temperatures for such a shallow setting, and also that thermal gradients were very steep near the surface. Preliminary isotopic studies indicate a magmatic source for sulphur, but the other fluid components are meteoric in origin (Ashley, 1982). Alunite and native sulphur are dominantly hypogene in these deposits. Supergene alunite that forms in some acid-sulphate alteration zones and leached cappings can be distinguished by stable isotope analysis and radiometric dating.

A Canadian Cordilleran Epithermal Model

A General Model. The western part of the Canadian Cordillera is a dominantly eugeoclinal region. Allochthonous volcanic terranes, flanking sedimentary basins, and their metamorphosed and intruded equivalents, were accreted during Mesozoic time against the ancestral continental margin of North America (Monger *et al.*, 1982). Most of the accreted terranes are only locally metamorphosed and large regions are only moderately deformed with little disruption of stratigraphic continuity. Within these terranes are numerous areas of subaerial rocks with related or younger, structurally-controlled, high-level plutons. These provide geological settings suitable for formation of epithermal deposits. The oldest known favourable host rocks are subaerial andesitic rocks that were deposited near the end of Early Jurassic island arc volcanism. Extensive Cretaceous and Tertiary to Recent continental volcanic rocks were deposited following Jurassic to Cretaceous accretion and consolidation of the Cordillera in a predominantly extensional tectonic regime with much major strike-slip faulting. Epithermal deposits in these rocks bear remarkable similarity to many Tertiary epithermal deposits in the southwestern United States.

Much of the Cordillera was extensively glaciated and is deeply dissected and eroded. Nevertheless, some sites of high-level hydrothermal activity and fossil hot spring deposits have survived. In the Toodoggone area, in northern British Columbia, for example, the recognition of 190 Ma alunite replacement deposits (Schroeter, 1982) and related epithermal deposits in rocks of Early Jurassic age (204-183 Ma) demonstrates the presence of pre-Tertiary epithermal deposits in the Canadian Cordillera. Recognition of old paleotopographic surfaces by means of attendant preserved hot spring deposits has important implications for exploration using depth-zoning models.

In a model developed from British Columbia deposits (Figure 5), there are three main hydrodynamic components that represent hydrothermal flow regimes in epithermal systems as illustrated by Berger and Eimon (1982). These are: (1) the near surface to hot spring discharge component; (2) the ascending, free-flowing, hydrothermal component that is open to surface (a physically "open" but chemically "closed" system); and (3) the intermittently sealed or constrained fluid flow component in which there are stacked hydrothermal cells and some lateral flow. The hot spring component with surface deposits of siliceous sinter, acid-sulphate and clay alteration zones, and underlying replacement alunite deposits has been described above. The ascending open hydrothermal component is essentially described by Buchanan's (1981) model, in which boiling and oxidation cause mineral deposition from ascending hydrothermal fluids in steep structurally-controlled conduits that remain open and provide unrestricted travel for fluids to the surface. The stacked hydrothermal cell component described in part by Berger and Eimon (1982), is more complicated. In this situation, hydrothermal fluids that encounter impermeable cap rocks, which restrict their upward flow, tend to migrate laterally. Similarly, in permeable zones, periodic constriction and self-sealing of hydrothermal conduits by precipitation of vein minerals, fault movements, dyke emplacement, or other mechanisms, restricts passage of fluids. When the system is sealed, fluid pressure builds until it exceeds the strength of the confining rocks and fracturing takes place as fluids break through to the surface. The resulting interplay of fluid pressures — from hydrostatic to those approaching lithostatic conditions — produces migrating boiling levels and hydrofracturing along the conduits. Rapid depressurization by hydro-fracturing or faulting can be accompanied by extensive breccia de-

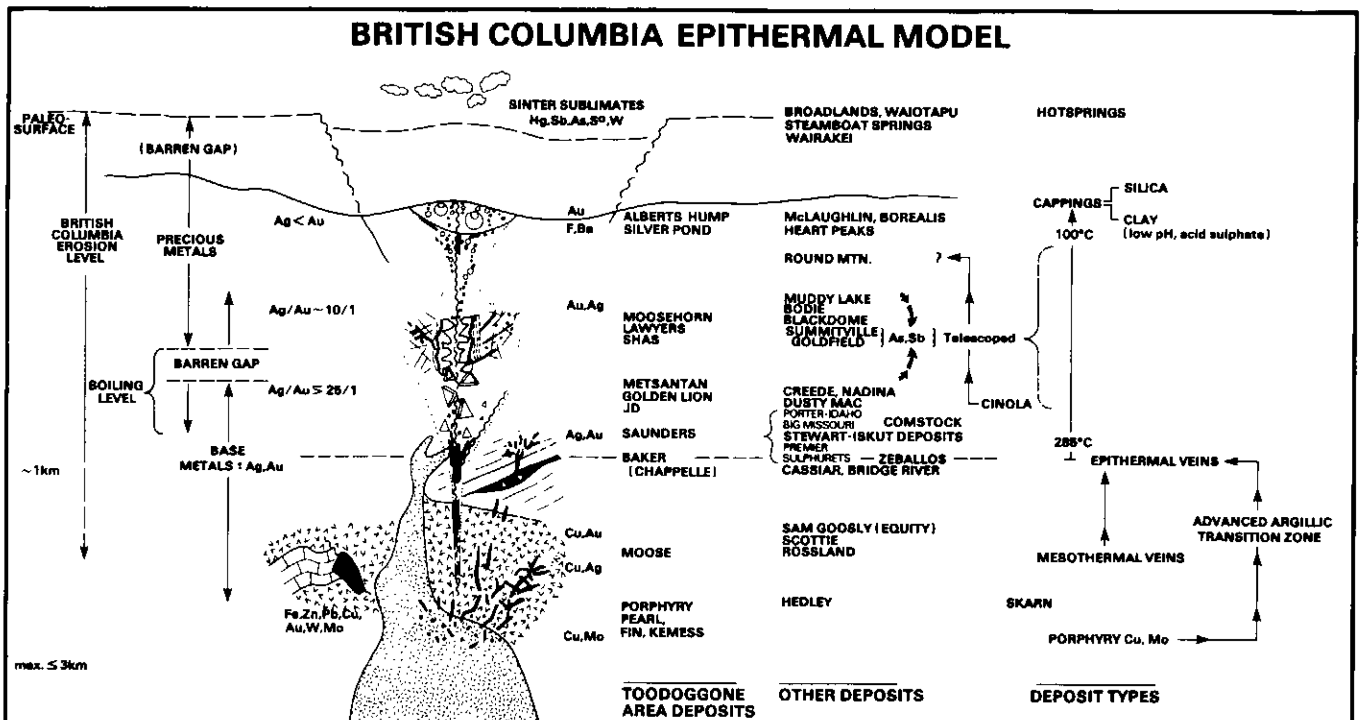

Figure 5 *British Columbia epithermal model. The model is based on studies of epithermal deposits in the Toodoggone area by T.G. Schroeter and A. Panteleyev, and comparisons with deposits elsewhere. The model infers a continuum exists from porphyry copper and skarn through transitional deposits, to epithermal veins, and hot spring discharge deposits.*

velopment and may lead to phreatic explosions at surface. In this type of flow regime, lateral, lithologically-controlled fluid flow can dominate when the system is sealed. The deposition sequence in veins is complicated by overlapping, periodically-repeated mineralization, and dissolution and replacement of earlier minerals. Older vein material is commonly broken and disrupted during later fracturing and brecciation. Wall rock interaction with fluids is more pronounced than in open, free-flowing systems, resulting in broader, more pervasive alteration envelopes around veins with both prograde and retrograde multicyclic alteration overprints.

The ore mineral zoning in epithermal deposits illustrated by Buchanan (1981) is part of a larger zoning pattern recognized long ago and described in a "reconstructed vein system" model by Emmons (1924). Ore zoning models, whether related to boiling levels or to progressive cooling away from magmatic fluid sources as proposed in older theories, predict that deeper vein deposits will contain base metals with some precious metals, and silver will increase in abundance upward. Above will be a zone with both gold and silver, and it will be capped by a zone containing minor amounts of gold in the form of electrum near the surface. At surface, porous rocks and sinter will contain a little cinnabar, arsenic, and antimony, and possibly some barite and fluorite. Rarely, these siliceous sinters contain gold in economic amounts.

The generalizations about precious metal zoning, as defined by silver to gold ratios in mine workings, rarely stand close scrutiny in epithermal districts, in individual deposits, or in orebodies. Zoning patterns are commonly inconsistent between epithermal deposits in the same district. Ore zones in these deposits tend to be erratic in distribution and grade, a feature that makes ore reserve calculations frustrating and difficult. For example, at the Silbak Premier Mine, one of the largest past producers in the Canadian Cordillera, the average silver to gold ratio within the same orebody of 23:1, varied from 112:1 to 5:1 over a vertical range of 400 metres (Grove, 1971). Gold content consistently increased with depth relative to silver, contrary to traditional expectations. Perhaps the only valid generalization about metal distributions in epithermal deposits is that base metals tend to increase with depth and silver is more abundant than gold. Silver to gold ratios are generally greater than one, and most are commonly 10:1 to 25:1, or greater.

Another zone invariably discovered during the course of mining operations or encountered during exploration is the "barren gap", one of which is shown on Figure 5. A barren gap, as shown by Emmons (1924), occurs below the bonanza gold and gold-silver deposits and above the deeper silver-rich and base metal zones. As Emmons (1924, p. 986) stated: "so many of precious-metal deposits of the Tertiary (epithermal) type pass downward abruptly into worthless gangue that this has come to be regarded as an outstanding characteristic". The explanation for barren gaps is not certain. They might represent the zones in which the deeper, hot, mildly reducing and alkaline, dilute chloride brines pass through the transition into oxidized, neutral to acid solutions; possibly no ore minerals are deposited in this environment. More likely, the barren gap is a zone where earlier deposited minerals are dissolved and remobilized during hypogene leaching (Brimhall, 1980). Periodic shifts between precipitation and dissolution can be expected as pH, redox, acidity, and fluid pressure conditions fluctuate in response to migrating boiling levels, self-sealing of conduits, and mixing of fluids.

British Columbia Epithermal Deposits

The model for epithermal deposits shown in Figure 5 is based in large part on study of the Jurassic deposits in the Toodoggone area of northern British Columbia. In this area much topographic relief and block faulting allow reconstruction of a large vertical range in hydrothermal systems, from their intrusive source areas to hot spring discharge sites. The highest structural levels, and sites of hot spring discharge are represented by the Alberts Hump and Silver Pond deposits. These are siliceous alunite-clay cappings that are analogous to fossil hot spring deposits and acid-sulphate alteration zones. At Alberts Hump, a number of these alunite-clay zones occur within an area of hydrothermal alteration about 6 kilometres in diameter, in which many small, fracture-controlled zones of high-grade gold-barite mineralization have been recently discovered.

A detailed study by Clark (1983) describes the vertical ordering of alteration zones from surface to depth as: alunite-quartz, clay-quartz-barite, clay-quartz, quartz-hematite, and quartz-pyrite (in propylitic rocks). This sequence, with the exception of abundant barite, bears a remarkable similarity to the Marysvale replacement alunite model of Cunningham *et al.* (1984). Similar alteration is evident in the Heart Peaks silver prospect, British Columbia, which contains amethystine quartz stockworks in Pliocene, or younger, rhyolites (Schroeter, 1985). These deposits are also similar to the Borealis Mine, Nevada, where a silicified wedge of ore with a capping of siliceous sinter is mined, and the McLaughlin deposit in California, where a Plio/Pleistocene hot spring has deposited 18 million tonnes of siliceous material containing 5.5 grams gold per tonne. This ore is adjacent to pits previously mined for mercury.

No large, low-grade disseminated hot spring deposit has been discovered in British Columbia, with the possible exception of the Cinola Mines (Babe) deposit. Cinola is a prospect in Miocene conglomerate and sandstone beds containing more than 30 million tonnes with about 2 grams gold per tonne. The mineralization occurs in a silicified zone, surrounded by argillic rocks and is localized along a major fault that has been intruded by a Miocene rhyolite dyke (Champigny and Sinclair, 1982). Cinola poses an intriguing problem in depth classification; it appears to have hot spring affinity but detailed examination of fluid inclusion, stratigraphic, and age data suggest a depth of formation of 1.1-1.8 kilometres (Shen *et al.*, 1982).

The main Toodoggone epithermal deposits are divided into two groups: those with amethystine quartz and little base metal content (Lawyers, Moosehorn, Shas), and the base metal-bearing quartz-carbonate vein deposits (Metsantan, Golden Lion, JD). These deposits resemble many other epithermal prospects or past producers in British Columbia such as Engineer, Blackdome, Nadina, Dusty Mac, and a number of occurrences in the Stewart-Iskut area. The Stewart area deposits, including the Silbak-Premier Mine, and 12 other large, former producing mines, and numerous smaller mines and prospects, are especially noteworthy for their variety of mineralization and regional zoning patterns. Most of the mine production came from gold-silver vein deposits that occur with andesitic volcanic and dyke rocks and are genetically related to Middle Jurassic felsic volcanism (Alldrick, 1985). All these British Columbia deposits have some features that resemble those of the well-known "classic" epithermal deposits in the southwestern United States, such as Round Mountain, Nevada; Bodie, California; Creede, Colorado; and the famous Comstock Lode, Nevada.

Deeper levels of hydrothermal activity in the Toodoggone area are represented by the pyritic, sericite-altered, and molybdenite-bearing Saunders prospect and by Baker Mine (Chappelle). Mineralization at Baker Mine is in quartz veins in faults in Triassic volcanic rocks that underlie the subaerial Jurassic rocks. The Moose, Porphyry Pearl, Fin, and Kemess deposits are spatially associated with intrusive rocks. Mineralization in these deposits is characteristic of the porphyry copper-molybdenum type but with enhanced amounts of gold and silver; large, low-grade zones of fracture-controlled galena, sphalerite, and gypsum veinlets suggest lower temperature, epithermal affinities. Elsewhere, some other epithermal deposits, such as those at Zeballos on Vancouver Island, also show a close spatial relationship with intrusive stocks (Sinclair and Hansen, 1983).

The other British Columbia deposits on Figure 5 that are shown to occur at deeper structural levels, can be considered to be "mesothermal" type. They are generally compact, crystalline white quartz or ribboned, graphitic quartz veins containing ankeritic carbonate minerals and some native gold, arsenopyrite, pyrite, pyrrhotite, base metal sulphides, and minor scheelite. Host rocks are commonly greenstone in strongly deformed terranes that have undergone greenschist-grade metamorphism. The veins tend to have relatively thin, carbonate-rich alteration envelopes containing quartz-sericite or quartz-pyrite-fuchsite-albite-chlorite-talc. Some mesothermal auriferous veins are devoid of quartz and contain massive, fine-grained intergrowths of pyrite, pyrrhotite, and minor base metal sulphides. These mesothermal-type veins are similar to the California motherlode veins (Nesbitt *et al.*, in prep.) or Archean lode gold deposits (Colvine *et al.*, 1984). Gold-bearing veins in the Cassiar and Bridge River areas are examples of mesothermal quartz, quartz-carbonate, and ribboned quartz-graphite veins associated with carbonate-sericite-fuchsite alteration in basic to ultrabasic host rocks. The veins in the Rossland area and the Scottie deposits are deeper-seated, auriferous, mesothermal-type pyrite-pyrrhotite chalcopyrite veins with related silicate alteration. Hedley is an arsenopyrite-rich skarn or tactite gold deposit.

Examples of the telescoped, acid-sulphate enargite-alunite-bearing orebodies are not known to occur in British Columbia. However, Sam Goosly deposit (Equity Silver Mine), an important silver, gold, copper, antimony, arsenic deposit with initial reserves of 28 million tonnes with 0.38% copper, 106 grams silver per tonne, 0.96 grams gold per tonne, and 0.085% antimony (Cyr *et al.*, 1984) is somewhat similar. The deposit was discovered in 1967 and can be regarded (Schroeter and Panteleyev, 1985) as a "transitional deposit" linking mineralization of the porphyry copper and epithermal types. The porphyry copper-epithermal transition deposits are Cu, Ag, Au ores containing abundant pyrite and arsenic-antimony minerals such as enargite and/or tetrahedrite. They are akin to hot acid sulphate aluminous epithermal deposits such as Goldfield, Nevada and Summitville, Colorado (Sillitoe, 1983). However, they are deeper-seated, more restricted "closed" systems spatially associated with intrusive rocks, and not sufficiently oxidized to produce extensive alunite or native sulphur. The transitional deposits contain higher temperature aluminous alteration minerals such as andalusite, pyrophyllite, diaspore, and commonly have peripheral or overprinted zones of sericite and kaolinite alteration. Fluid inclusion homogenization temperatures approach those of porphyry copper deposits but show a larger temperature range. Fluids are generally more saline than those of epithermal deposits, but display a broad range from relatively concentrated to dilute. Shen and Sinclair (1982) and Wojdak and Sinclair (1984) described temperatures of mineralization at Equity Silver that range from over 400°C to about 200°C, and salinities in ore veins up to 22 wt.% equivalent NaCl. A number of the enargite deposits described by Sillitoe (1983) could be considered to be transitional types, as are parts of the Butte, Montana deposit.

Summary

Figure 5 presents the comparative position of epithermal deposits relative to other major genetic types of deposits. Mineral deposits in a volcanic intrusive setting are shown to form a continuum from intrusive-related porphyry copper and skarn to hot spring discharge deposits. Clearly there will be gaps between deposits and neither all the ore fluids nor all the metals will be derived from the magmas. Further from intrusive stocks, meteoric fluids will probably dominate the ore-forming solutions and magmatic activity will simply provide heat to drive the convecting hydrothermal systems. Epithermal deposits form at high structural levels, at some distance from intrusions, except perhaps minor dykes. Temperatures would be less than 285°C, within the thermal stability limit of kaolinite. Higher temperatures occur in the deeper, transitional deposits and the telescoped, aluminous, acid-sulphate epithermal deposits. Epithermal hydrothermal systems produce extensive high level argillic zones and solfateric near-surface deposits of Hg, Sb, As, barite, fluorite and native sulphur. These mineral occurrences are indicators of potential bonanza gold and gold-silver ores at depth, ideally at depths of less than 1,000 metres.

Future Trends

The search for epithermal-type hydrothermal systems will be extended from the Mesozoic and younger, primarily subaerial volcanic terranes to other volcanic terranes, areas with subvolcanic and high level plutonic intrusions, and sedimentary terranes of the Cordillera. The sedimentary terranes, including miogeoclinal rocks of the eastern tectonic belts, will be explored for sediment-hosted, fine-grained disseminated gold deposits in thin-bedded calcareous rocks, shales and phyllites. Deposits in these rocks, similar to the Carlin, Nevada and other deposits in the southwestern US and the manto-type deposits in Mexico, are considered by many to have formed from epithermal-type hydrothermal systems (Bonham and Giles, 1983).

In addition to epithermal veins, the search will continue for large tonnage deposits suitable for open-pit mining. For example, Westmin Resources Limited recently announced reserves of over 4 million tonnes grading 2.43 grams gold per tonne and 110.4 grams silver per tonne in the Old Glory Hole area at Silbak Premier Mine in the Stewart area, where over 56 tonnes of gold and 1,270 tonnes of silver were recovered in the period 1918–1976, mainly from underground workings.

Innovative planning and research to assess the potential of heap or dump leaching might also lead to economic success. The attraction of leaching processes is that diffuse epithermal mineralization, low-grade stockpiles, or old waste dumps that are suitable to bulk mining and leaching extraction methods, might become economically viable with gold concentrations of only 1-2 ppm. In the Canadian Cordillera, the temperate climate and high rainfall might restrict leaching to seasonal operations or batch leaching, possible under cover. The economic success of leach extraction of gold and silver from ores with 0.7-1.4 ppm gold at elevations of 1,675 metres near Zortman-Landusky in the Little Rocky Mountains of Montana provides an important example and an inspiration for possibilities in the Canadian Cordillera (Chamberlain and Pojar, 1984). Possibly the biggest inhibitor to viable operations in the Canadian Cordillera will not be climate but rather, lack of well-developed zones of weathering oxidation in the extensively-glaciated terrane.

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