

# EPITHERMAL GOLD DEPOSITS

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## Abstract

Epithermal Au ( $\pm$ Ag) deposits form in the near-surface environment, from hydrothermal systems typically within 1.5 km of the Earth's surface. They are commonly found associated with centres of magmatism and volcanism, but form also in shallow marine settings. Hot-spring deposits and both liquid- and vapour-dominated geothermal systems are commonly associated with epithermal deposits. Epithermal Au deposits are commonly considered to comprise one of three subtypes: high sulphidation, intermediate sulphidation, and low sulphidation, each denoted by characteristic alteration mineral assemblages, occurrences, textures, and, in some cases, characteristic suites of associated geochemical elements (e.g. Hg, Sb, As, and Tl). Base metal (Cu, Pb, and Zn) and sulphide minerals may also occur in addition to pyrite and native Au or electrum. In some epithermal deposits, notably those of the intermediate-sulphidation subtype, base metal sulphides may comprise a significant ore constituent.

Canadian Au production from epithermal deposits has been minor (<5%), compared to that from transitional and intrusion-related Au deposits, or to other lode Au deposits. The shallow origin of epithermal Au deposits makes them more susceptible to erosion, and, accordingly, epithermal Au deposits have represented a high-grade, readily mineable, exploration target largely in Tertiary and younger volcanic centres, including the Cordillera. However, a number of older epithermal Au deposits have also been discovered, including several Proterozoic examples in Canada. Thus, older terranes need not be excluded entirely from exploration.

Modern geothermal and volcanic systems provide natural laboratories for the study of epithermal deposits, guiding theoretical models and laboratory experiments, and expanding our understanding of potential environments and vectors to mineralized systems. Yet, a principal, unanswered question still remains: do rich Au deposits form from Au-rich sources, or from exceptionally efficient mechanisms or processes of Au precipitation?

## Résumé

Les gîtes d'or ( $\pm$  argent) épithermaux se forment dans le milieu subsuperficiel, de manière caractéristique à moins de 1,5 km de la surface de la Terre. Ils sont couramment présents dans des centres magmatiques ou volcaniques à la surface du globe, mais se forment également dans des cadres marins de faible profondeur. Des dépôts de sources thermales ainsi que des systèmes géothermiques tant à dominante liquide qu'à dominante vapeur sont couramment associés aux gîtes épithermaux. Deux sous-types de gîtes sont définis d'après les minéraux d'altération communs qu'ils renferment: les gîtes à quartz-(kaolinite)-alunite (QAL) formés à partir de fluides acides avec un important apport magmatique et les gîtes à adulaire-séricite (ADS) formés à partir de fluides quasi neutres en grande partie composés d'eau météorique. Des métaux communs peuvent être présents dans l'un ou l'autre sous-type.

La production canadienne d'or tirée de gîtes épithermaux est mineure (< 5%), mais ailleurs dans le monde, cette classe de gîtes à teneur élevée et facilement exploitables constitue une cible d'exploration. Les gîtes épithermaux profonds ou associés à des intrusions ont fourni une plus importante contribution à la production canadienne d'or. La faible profondeur à laquelle se forment les gîtes d'or épithermaux fait en sorte qu'ils sont davantage susceptibles d'érosion et ils ont par conséquent tendance à être découverts dans des terrains plus récents. De toute évidence, un enfouissement rapide a préservé un certain nombre de gîtes d'or épithermaux dans des terrains plus anciens, dont on trouve des exemples dans des roches du Protérozoïque. Ces occurrences permettent d'afficher un certain optimisme quant à l'exploration de terrains plus anciens au Canada.

Les systèmes géothermiques contemporains constituent des laboratoires naturels d'étude des gîtes épithermaux ainsi que des guides pour l'élaboration de modèles théoriques et d'expériences à mener en laboratoire. De telles études permettent continuellement d'améliorer la compréhension et fournissent des guides pour l'exploration; chacune contribuant à répondre à l'importante question qui reste sans réponse : les riches gîtes se forment-ils à partir de sources riches ou sont-ils attribuables à des facteurs déterminés par un processus de précipitation ou de concentration?

## Definition

### *Simplified Definition*

Epithermal deposits of Au ( $\pm$  Ag) comprise veins and disseminations near the Earth's surface ( $\leq 1.5$  km), in volcanic and sedimentary rocks, sediments, and, in some cases, also in metamorphic rocks. The deposits may be found in association with hot springs and frequently occur at centres of young volcanism. The ores are dominated primarily by precious metals (Au, Ag), but some deposits may also contain variable amounts base metals such as Cu, Pb, and Zn.

### *Scientific Definition*

Epithermal Au deposits are a type of lode deposit (e.g. Poulsen, 1996; Poulsen et al., 2000) consisting of economic

concentrations of Au ( $\pm$  Ag and base metals). These deposits form in a variety of host rocks from hydrothermal fluids, primarily by replacement (i.e. by solution and reprecipitation), or by open-space filling (e.g. veins, breccias, pore spaces). The form of deposits originating by open-space filling typically reflects that of the structural control of the hydrothermal fluids (planar vs. irregular fractures, etc). The deposits are commonly young, generally Tertiary or Quaternary. They may be of similar age as their host rocks when these are volcanic in origin, or (typically) younger than their host.

Early workers (e.g. Lindgren, 1922, 1933; Emmons, 1924) emphasized a broad depth-zoning classification of hydrothermal metal deposits in which epithermal deposits were interpreted to have formed in a 'shallow' regime, qual-

itatively on the order of  $\leq 1500$  m. Depth is, however, challenging to quantify, except where a datum (e.g. the Earth's surface) may be recognized, or a stratigraphic reconstruction made. Depth may be inferred, for example, from a depth-to-boiling curve, plus evidence of boiling in fluid inclusions and an estimated formation temperature based on a geothermometer (e.g. trace element or stable isotope distributions), or, simply, from textures indicative of boiling-induced supersaturation (e.g. quartz pseudomorphs of bladed calcite). In any case, the generally accepted shallow origin of epithermal Au deposits is a central (and genetically important) characteristic. This environment is marked by rapid changes in temperature and pressure of the hydrothermal fluids that may be accompanied by boiling and mixing with other fluids, causing changes in pH and oxidation state and, consequently, precipitation of Au (and other metals). Epithermal deposits may also be characterized by the presence of other volatile accessory elements (Hg, Sb, Tl, etc.).

Many geologists today regard 'epithermal' Au deposits to be primarily associated with continental volcanism or magmatism, although similar processes of ore deposition occur in other, near-surface environments (e.g. seafloor volcanogenic massive sulphide (VMS) deposits, submarine volcanic arc systems, and non-volcanic vein deposits; see Gosselin and Dubé, 2005a-d; Dubé et al., 2007). These other deposits, especially those with similar characteristics from marine environments, may also be considered epithermal deposits in a broad sense. Many extensive reviews of epithermal deposits, among them Buchanan (1981), Hayba et al. (1985), Berger and Bethke (1986), Heald et al. (1987), White and Hedenquist (1990), Arribas (1995), Richards (1995), Hedenquist et al. (1996, 2000), and Cooke and Simmons (2000) have provided a wealth of background information. This chapter will largely focus on the continental environment, emphasizing young deposits in the Canadian Cordillera, as well as examples of epithermal Au deposits found in older terranes elsewhere in Canada.

Epithermal Au deposits are distinguished on the basis of the sulphidation state of the sulphide mineralogy as belonging to one of three subtypes: (1) high sulphidation (previously called quartz-(kaolinite)-alunite, alunite-kaolinite, enargite-Au, or high sulfur: Ashley, 1982; Hedenquist, 1987; Bonham, 1988); (2) intermediate sulphidation (Hedenquist et al., 2000); or (3) low sulphidation (previously called adularia-sericite). High-sulphidation subtype deposits usually occur close to magmatic sources of heat and volatiles, and form from acidic hydrothermal fluids containing magmatic S, C, and Cl. Low-sulphidation subtype fluids are thought to be near-neutral, dominated by meteoric waters, but containing some magmatic C and S. In addition, some geologists also refer to 'hot-spring' deposits as an additional subtype of epithermal deposit that may form as surface expressions of hydrothermal systems, typically of the low-sulphidation subtype sometimes associated with acidic, steam-heated alteration zones. See Henley et al. (1984), Hayba et al. (1985), Heald et al. (1987), Hedenquist (1987), Bonham (1988), Berger and Henley (1989), and Panteleyev (1996a-c) for discussions and original definition of these terms. Hedenquist et al. (2000) is recommended for a more recent and very comprehensive summary of current usage, classification, and deposit characteristics.

The Blackdome and most of the deposits in the Toodoggone River camp in British Columbia, and the Mt. Skukum deposit, Yukon, are among the best Canadian examples of volcanic-hosted, low-sulphidation subtype epithermal Au deposits (Table 1). The Cinola deposit, British Columbia (Champigny and Sinclair, 1982), hosted by sedimentary rocks, is an example of a low-sulphidation hot-spring deposit (in particular, its upper part). High-sulphidation deposits are less well represented in Canada, but include the volcanic-hosted Al deposit, Toodoggone River camp, British Columbia and the metamorphosed Hope Brook deposit, Nova Scotia (Table 1). Numerous areas of advanced argillic alteration mineral assemblages and associated Au prospects formed by high-sulphidation systems of Neoproterozoic age are also known in the Burin Peninsula, Newfoundland (e.g. Hickey's Pond: O'Brien et al., 1999). The locations of these and other Canadian epithermal deposits or districts, and selected deposits elsewhere in the world, are shown in Figures 1 and 2, respectively, and include, especially, those deposits or districts noted in the text.

Numerous examples of both low-sulphidation and high-sulphidation deposits in volcanic and sedimentary host rocks exist world wide, especially in younger volcanic terranes. Classic examples of the high-sulphidation subtype include Summitville, Colorado (Bethke et al., 2005) and Nansatsu, Japan (Hedenquist et al., 1994). The Creede district, Colorado (e.g. Heald et al., 1987) and Hishikari, Japan (Izawa et al., 1990; Hayashi et al., 2001, and references therein) are good examples of volcanic-hosted low-sulphidation subtype deposits. Others are noted below.

#### *Diagnostic Features of Epithermal Gold Deposits*

Geological, mineralogical, and geochemical features of epithermal Au deposits are listed for each of three deposit subtypes in Table 2. Distinctive features typically present include key alteration mineral assemblages (low sulphidation: sericite, adularia, kaolinite, calcite, rhodochrosite, Fe-chlorite, quartz; high sulphidation: alunite, kaolinite, pyrophyllite, sericite, adularia (illite), chlorite, barite; Table 2), ore mineral assemblages (low sulphidation: electrum, Hg-Sb-As sulphides, base metal sulphides; high sulphidation: native Au, electrum, tellurides, base metal sulphides; Table 2), geological evidence for shallow emplacement: sinter deposits, fluid inclusion or textural evidence (e.g. lamellar calcite, or their quartz pseudomorphs) for boiling, hydrothermal breccias and eruption deposits, open-space crustiform veins, and marked  $^{18}\text{O}$  depletion of wall rocks. Vertical zoning of alteration minerals, lower Au:Ag ratios in electrum with depth, and spatial and temporal separation of Au and abundant base metals are also characteristic (though not universal) of epithermal Au deposits.

Although most known epithermal Au deposits are Tertiary in age, the mineralogical and geological characteristics noted above have led to the recognition of much older epithermal deposits, including recrystallized and deformed examples in metamorphic terranes. Although high-sulphidation-related alteration is distinctive, corroboration of an epithermal setting by low  $^{18}\text{O}/^{16}\text{O}$  ratios can, particularly for the low-sulphidation subtype, provide a unique record of alteration by meteoric waters, one that survives metamorphism and requires a shallow origin. For example, the Carolina Slate

TABLE 1. Comparative mineralogical, geological, and production data for selected epithermal Au deposits in Canada and several non-Canadian type examples.\*

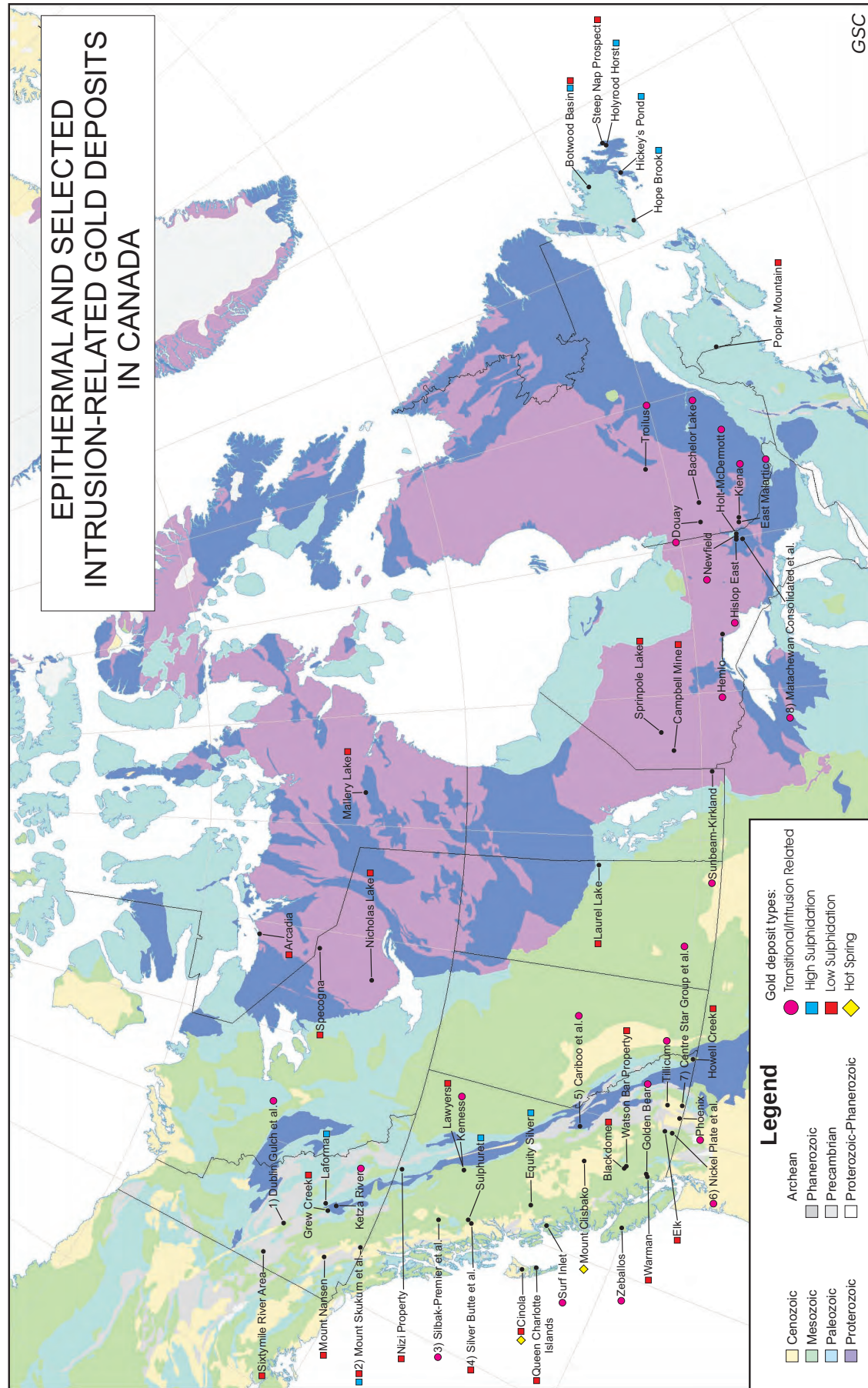
| District and/or deposit                                                                       | Age <sup>1</sup><br>Host [Min.] | Size <sup>2</sup> (R+P)<br>Ore <sup>5</sup> AU <sup>6</sup> | Grade <sup>3</sup> Ag/Au | Base<br>Metal | %S     | Ad      | Al                | Cpy             | En | Ss | Ags | Sp | Gn | Ba | Fl | Rc | Cc | Ank | Carbonates | Host rock          | Alt <sup>n.7</sup><br>vn → w.r. | Form <sup>8</sup> | Selected<br>Refs. |
|-----------------------------------------------------------------------------------------------|---------------------------------|-------------------------------------------------------------|--------------------------|---------------|--------|---------|-------------------|-----------------|----|----|-----|----|----|----|----|----|----|-----|------------|--------------------|---------------------------------|-------------------|-------------------|
| <b>HIGH-SULPHIDATION TYPE:<sup>9</sup> Volcanic host rocks</b>                                |                                 |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Toodoggone River, B.C.                                                                        | 189-198;182                     | 0.348                                                       | 3.21                     | 9.6           |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            | and./dacite        | Si/A                            | vn                | 10,11,29,30,34    |
| Al (Bonanza; Thesis)                                                                          | [196]                           | 0.053                                                       | 0.55                     | 10.4          | x      |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            | andesite           |                                 | vn,bx             | 29                |
| Equity Silver, B.C. <sup>14</sup>                                                             | [190-197]                       | 31.42                                                       | 24.41                    | 4.2           | 128.2  | x       |                   |                 |    |    |     |    |    |    |    |    |    |     |            | dacite/tuff/congl. | A                               | vn,st,diss.       | 17,18,19          |
| Summitville, Colorado                                                                         | 57.2 [≥48;57.2]                 | 83.51                                                       | 3.5                      |               | 1.2    | x       | 57                |                 |    |    |     |    |    |    |    |    |    |     |            | qtz. Latite        | Vgy-Si/Qtz-A/A                  | repl., vn         | 28,31             |
| Nansatsu, Japan                                                                               | 20.2-22.0 [22.3]                |                                                             |                          |               | 3-6    | 0.1-1.0 | x                 |                 |    |    |     |    |    |    |    |    |    |     |            | andesite           | Vgy-Si/Al-A/Ph/P                | repl.             | 32                |
| El Indio, Chile <sup>19</sup>                                                                 | 3.4-7.6 [2.7-5.5]               |                                                             |                          |               | >18    |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            | rhodacite          | Si/Ph-A (Al-A)                  | vn,bx             | 35,36             |
|                                                                                               | 13.7 [8.6]                      | 8.7                                                         | 108                      | 1.7-2.18      | 0.5-10 | XX      | ≤30 <sup>11</sup> |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| <b>INTERMEDIATE-SULPHIDATION TYPE (possible example; variant of low-sulphidation subtype)</b> |                                 |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Stewart-Iskut region, B.C.                                                                    | 210                             |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Silbak-Premier                                                                                | [194.8?]                        | 9.622                                                       | 66.24                    | 7.0           | 22.6   | XX      | ≤5 <sup>12</sup>  | X <sup>13</sup> |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| <b>LOW-SULPHIDATION TYPE: Volcanic and plutonic host rocks</b>                                |                                 |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Mt. Skukum, Y.T.                                                                              | 53.2 [50.7]                     | 0.200                                                       | 2.49                     | 25.0          | 0.9    |         | <1                | x               |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Mt. Nansen, Y.T.                                                                              | Tertiary                        | 0.288                                                       | 3.15                     | 11.1          | 39.0   |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Laforma, Y.T.                                                                                 | >140 [78?]                      | 0.191                                                       | 2.13                     | 11.2          |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Venus, Y.T.                                                                                   | L. Jur.                         | >0.07                                                       | >0.66                    | 9.3           | 26.5   | XX      | 15-60             |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Toodoggone River, B.C.                                                                        | 189-198;182                     |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Lawyers                                                                                       | [180]                           | 0.880                                                       | 6.73                     | 7.4           | 46.7   | x       |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Baker (Chapelle)                                                                              |                                 | 0.055                                                       | 1.05                     | 19.5          | 9.1    |         | 3-15              |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Blackdome, B.C.                                                                               | Eocene [≥24,<51.5]              | 0.368                                                       | 7.35                     | 20.6          | 3.1    | x       | ≤5                |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Stewart-Iskut region, B.C.                                                                    | 210                             |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Sulphurets (Snowfield)                                                                        | [192.7]                         | 25                                                          | 0.78                     | 2.4           | 0.6    | x       |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Creede, Colorado                                                                              | Tertiary                        | 1.4                                                         | 21.0                     | 1.5           | 400    | x       |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| <b>LOW-SULPHIDATION TYPE: Sedimentary and/or mixed host rocks</b>                             |                                 |                                                             |                          |               |        |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Cinola, B.C.                                                                                  | Tert./Cret. [14]                | 23.80                                                       | 58.31                    | 2.45          | 2      | x       | ≤10               |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Dusty Mac, B.C.                                                                               | Eocene                          | 0.093                                                       | 0.60                     | 7.2           | 21.5   | x       | ≤15               |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |
| Hishikari, Japan                                                                              | 0.51-1.78/Cret. [0.8-1.0]       | 121.7                                                       | 70                       | 1.27          | x      |         |                   |                 |    |    |     |    |    |    |    |    |    |     |            |                    |                                 |                   |                   |

\* Principal deposits plus several others selected to represent part of the spectrum of variation in type and setting, modified from Taylor (1996).

1. Based on reported mineral ages; Ma., exclusive of uncertainty limits. Host-age of host rocks; [Min.] = age of mineralization. 2. P = cumulative production; R = reserves; 3. Average grade in g/t; 4. characteristic; in addition to quartz (+pyrite±sericitic±clays); 5. tonnes of ore x10<sup>6</sup>; 6. grams of gold (Au) x10<sup>6</sup>; 7. Alteration facies; vein (vn) to wall rock (w.r.); Vgy-Si; vuggy silica; Qtz; quartz; Al; alunite (advanced argillic); Si; silicification; K; potassic; Ph; phyllic (sericitic); A; argillic/advanced argillic; P; propylitic (sequence from vein to wall rock); 8. Form of deposit (in order of importance) vn, vein; bx, breccia; st, stockwork; diss. disseminated; repl., replacement; 9. Classification is based on available data; uncertain in some cases; 10. main gold deposition probably not from alunite-kaolinite type system, *sensu stricto*, see text; 11. older, alunite-associated (Cu) veins contain 30-90% sulphide; 12. base metal-rich veins and breccias contain 20-45% sulphide; 13. potassium feldspar; species not confirmed; 14. contains metamorphosed advanced argillic mineral assemblage; low-pH conditions approached those of magmatic-hydrothermal QAL subtype deposits; 15. in oxidized ore.

Abbreviations: %S\*, per cent sulphide; Ad, adularia; Al, alunite; Cpy, chalcocopyrite; En, enargite; Ss, sulphosalts (e.g., tennantite-tetrahedrite); Ags, silver sulphides; Sp, sphalerite; Gn, galena; Ba, barite; Fl, fluorite; CO<sub>3</sub>, carbonate; Rc rhodochrosite; Cc, calcite; Ank, ankerite; XX = abundant; X = present; x = minor to rare; blank = absent or unknown; and = andesite; bsit. = basalt; congl. = conglomerate; s.s. = sandstone; lms. = limestone; sh. = shale; Tert. = Tertiary; Cret. = Cretaceous; L. Jur. = Lower Jurassic; NB: [ ] = not in paragenetic association with Au.

References: 1) Schroeter, 1986; 2) Schroeter, 1985; 3) Schroeter, 1982; 4) D. Rennie, 1986, written comm.; 5) Walton, 1986; 6) Walton and Nesbitt, 1986; 7) McDonald et al., 1986; 8) McDonald and Godwin, 1986; 9) Pride and Clark, 1985; 10) Clark and Williams-Jones, 1986; 11) Schroeter, 1986; 12) Andrew et al., 1986; 13) Barr et al., 1986; 14) Morin and Downing, 1984; 15) Duke and Godwin, 1986; 16) McFall, 1981; 17) Shen and Sinclair, 1982; 18) Cyr et al., 1984; 19) Wojdak and Sinclair, 1984; 20) Love, 1989; 21) McDonald, 1990; 22) Mosier et al., 1985; 23) Faulkner, 1986; 24) Vull mir et al., 1986; 25) Champigny and Sinclair, 1982; 26) Vivian et al., 1987; 27) Christie, 1989; 28) Heald et al., 1987; 29) Diakow et al., 1993; 30) Clark and Williams-Jones, 1991; 31) Stoffregen, 1987; 32) Hedenquist et al., 1994; 33) McInnes et al., 1990; 34) B.C. Geol. Survey (MINFILE/pc), 1992; 35) Jannas et al., 1990; 36) Siddeley and Aranea, 1986; 37) Izawa et al., 1990; 38) Bakken and Einandi, 1986; 39) Church, 1973; 40) Margolis, 1993.

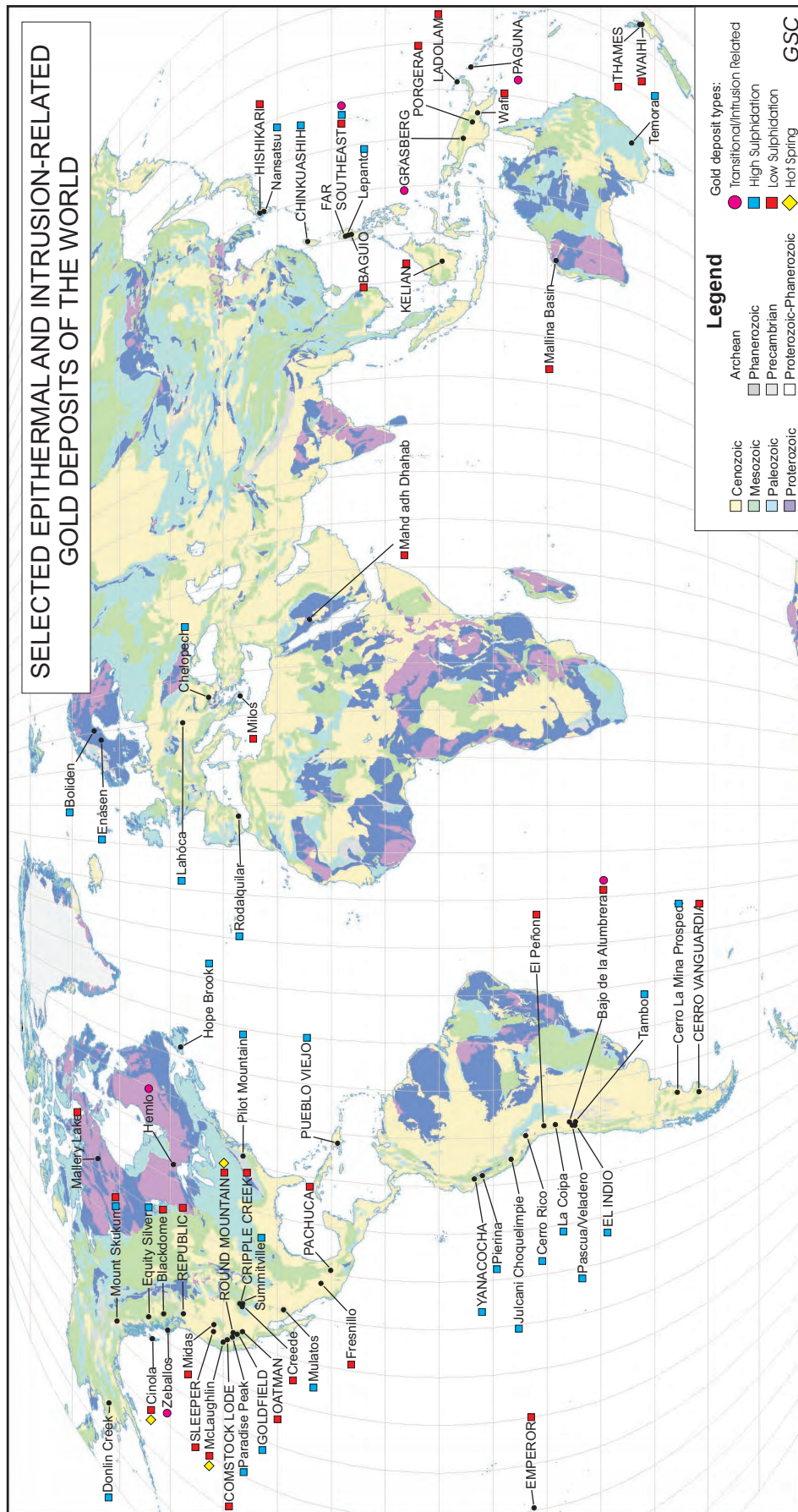


**All Mines listed are largest deposits for area; in cases where more than one deposit is located, "et al." has been indicated as follows:**

1) Dublin Gulch et al., includes: Dublin Gulch, Eagle Zone, Brewery Creek; 2) Mount Skukum et al., includes: Mount Skukum, Skukum Creek, Stonehouse, Ship, Twin Zone, Scottie, Salmon Gold, Premier, Bush, Silbak, Premier Gold; 4) Silver Butte et al., includes: Silver Butte, SIB, Goldwedge; 5) Cariboo et al., includes: Cariboo, Aurum, QR, Dome, Quesnel River; 6) Nickel Plate et al., includes: Nickel Plate, Hedley; 7) Centre Star Group et al., includes: Centre Star Group, Josie, Le Roi No. 2; 8) Malachewan Consolidated et al., includes: Malachewan Consolidated, Young-Davidson, Ryan Lake.

References: Brown and Cameron, 1999; Dube et al., 1998; Gosselin and Dube, 2005a,b,c; 2005a,b,d; Panteleyev, 1996a,b,c; Poulson et al., 2000; Taylor, 1996, this paper; Turner et al., 2003.

FIGURE 1. Location of selected Canadian epithermal Au deposits and prominent examples elsewhere in the world, classified by subtype as referred to in the text. Names and locations of deposits from sources are listed.



**References:** Arancibia et al., 2006; Bethke et al., 2005; Carman, 2003; Deyell et al., 2005; Dubé et al., 1998; Fifiarek and Rye, 2005; Goldfarb et al., 2004; Gosselin and Dubé, 2005a,c; Hedenquist et al., 2000; Huston et al., 2002; Klein and Criss, 1988; Naden et al., 2005; Panteleyev, 1996a,b,c, 2005a,b; Poulsen, 1996, 2000; Sillitoe, 1992, 1997; Taylor, 1996, this paper; Turner et al., 2003.

**N.B.:** Giant and Bonanza Gold deposits indicated by capitalization of deposit name, e.g., EL INDIO.

**FIGURE 2.** Global distribution of selected Canadian and non-Canadian epithermal and intrusion-related Au deposits of the world. The association of many (young) deposits with the circum-Pacific Belt emphasizes their genetic link to magmatic centres. Giant or Bonanza deposits (Sillitoe, 1992) are labeled in uppercase font. Deposits shown include those noted in the text or represented in accompanying figures. Names and locations of deposits from sources are listed.

TABLE 2. Summary of geological setting, definitive characteristics<sup>1</sup> and several examples of typical epithermal Au deposit subtypes.

|                                                        | HIGH-SULPHIDATION subtype                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                       | LOW-SULPHIDATION subtype                                                                                                                                                                                                           |  |
|--------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
|                                                        | Hosted in volcanic rocks                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Hosted in volcanic and plutonic rocks                                                                                                                                                                                                                                                 | Hosted in sedimentary and mixed host rocks                                                                                                                                                                                         |  |
| Geological setting                                     | volcanic terrane, often in caldera-filling volcanoclastic rocks; hot spring deposits and acid lakes may be associated                                                                                                                                                                                                                                                                                                                                                                     | Spatially related to intrusive centre; veins in major faults, locally ring fracture type faults; hot springs may be present                                                                                                                                                           | In calcareous to clastic sedimentary rocks; may be at depth by magma; can form at variety of depths                                                                                                                                |  |
| Ore mineralogy                                         | native gold, electrum, tellurides; magmatic-hydrothermal: (+bn), en, tennantite, cv, sp, gn; Cu typically > Zn, Pb; Au-stage may be distinct, base-metal poor; steam-heated: base-metal poor; gangue: quartz (vuggy silica), barite                                                                                                                                                                                                                                                       | electrum (lower Au/Ag with depth), gold; sulphides include: sp, gn, cpy, ss; sulphosalts; gangue: quartz, adularia, calcite, chlorite; $\pm$ barite, anhydrite in deeper deposits variable metal content, high sulphide veins closer to intrusions                                    | gold (micrometre): within or on sulphides (e.g. pyrite unoxidized ore), native (in oxidized ore), electrum, Hg-Sb-sulphides, pyrite, minor base metals; gangue: quartz, calcite                                                    |  |
| Alteration mineralogy                                  | advanced argillic + alunite, kaolinite, pyrophyllite (deeper); $\pm$ sericite (illite); adularia, carbonate absent; chlorite and Mn-minerals rare; no selenides; barite with Au; steam-heated: vertical zoning                                                                                                                                                                                                                                                                            | sericitic replaces argillic facies (adularia $\pm$ sericite $\pm$ kaolinite); Fe-chlorite, Mn-minerals, selenides present; carbonate and/or rhodochrosite) may be abundant, lamellar if boiling occurred; quartz-kaolinite-alunite-subtype minerals possible steam-heated zone; clays | silicification, decalcification, sericitization, sulphidation; alteration zones may be controlled by stratigraphic permeability rather than by faults and fractures; quartz (may be chalcedonic)-sericite (illite)-montmorillonite |  |
| Host rocks                                             | silicic to intermediate (andesite)                                                                                                                                                                                                                                                                                                                                                                                                                                                        | intermediate to silicic intrusive/extrusive rocks                                                                                                                                                                                                                                     | felsic intrusions; most sedimentary rocks except massive carbonates (hosts to mantos and skarns)                                                                                                                                   |  |
| <sup>18</sup> O/ <sup>16</sup> O - shift in wall rocks | may be less pronounced, or superposed on earlier high- <sup>18</sup> O alteration                                                                                                                                                                                                                                                                                                                                                                                                         | moderate to large; pronounced in and immediately adjacent to veins                                                                                                                                                                                                                    | very limited <sup>18</sup> O-shift of altered rocks, if present at all                                                                                                                                                             |  |
| C-H-S isotopes                                         | magmatic fluids indicated ( $\delta^{13}\text{C}_{\text{CO}_2} \approx -5\pm 2$ ; $\delta\text{D}_{\text{H}_2\text{O}} \approx -35\pm 10$ ; $\delta^{18}\text{O}_{\text{H}_2\text{O}} \approx +7\pm 2$ ; $\delta^{34}\text{S}_{\text{S}} \approx 0$ ); magmatic-hydrothermal alunite $\delta^{34}\text{S}$ -sulphide minerals; $\delta\text{D} \approx -35\pm 10$ ; steam-heated alunite $\delta^{34}\text{S} \approx$ sulphides, $\delta^{18}\text{O}$ data indicate hydrothermal origin | magmatic water (H <sub>2</sub> O) may be obscured by mixing; surface waters dominate; C, S typically indicate a magmatic source, but mixtures with wall rock derived C, S possible                                                                                                    | hydrogen isotope data (sericite, clays, fluid inclusions) in some cases indicate presence of evolved surface waters; organic carbon ( $\delta^{13}\text{C} \approx -26\pm 2$ ) may be derived from wall rocks                      |  |
| Ore fluids (examples from fluid inclusion studies)     | 160-240°C; $\leq 1$ wt. % NaCl (late fluids); possibly to 30 wt. % NaCl in early fluids; boiling common; (Nansatsu district, Japan; Hedenquist et al., 1994)                                                                                                                                                                                                                                                                                                                              | sulphide-poor: 180-31°C, $\leq 1$ wt. % NaCl, about 1.0 molal CO <sub>2</sub> (Mt. Skukum: McDonald, 1987) sulphide-rich: ave. 25°C, <1 to 4 wt. % NaCl (Silbak-Premier: McDonald, 1990)                                                                                              | bimodal: 150-160 (most); 270-280°C, $\leq 15$ wt. % NaCl; nonboiling: (Cinola: Shen et al., 1982); 230-250°C, $\leq 1$ wt. % NaCl; nonboiling (Dusty Mac: Zhang et al., 1989)                                                      |  |
| Age of mineralization and host rocks                   | host rocks and mineralization of similar age                                                                                                                                                                                                                                                                                                                                                                                                                                              | mineralization variably younger (>1 Ma) than host rocks                                                                                                                                                                                                                               | mineralization variably younger (>1 Ma) than host rocks                                                                                                                                                                            |  |
| Deposit size                                           | small areal extent (e.g. 1 km <sup>2</sup> ) and size (e.g. 2500-3500 kg Au)                                                                                                                                                                                                                                                                                                                                                                                                              | may occur over large area (e.g. several tens of km <sup>2</sup> ); may be large (e.g. 100 000 kg Au).                                                                                                                                                                                 | may have large areal extent (e.g. >>1 km <sup>2</sup> ), large size (e.g. 58 000 kg Au), low grades (e.g. 2.5 g/t)                                                                                                                 |  |
| Examples Canadian                                      | Equity Silver, B.C.; Mt. Skukum, Yukon (only: alunite 'cap')<br>Al deposit, Toadoggonne River, B.C.                                                                                                                                                                                                                                                                                                                                                                                       | Blackdome, B.C.; Mt. Skukum, Yukon (Cirque vein)<br>Silbak-Premier, B.C. (intermediate sulphidation)                                                                                                                                                                                  | Cinola, B.C.                                                                                                                                                                                                                       |  |
| Foreign                                                | Summitville, Colorado<br>Kasuga, Japan                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Creede, Colorado (intermediate sulphidation)                                                                                                                                                                                                                                          | Hishikari, Japan                                                                                                                                                                                                                   |  |
| Modern analogues:                                      | Matsukawa, Japan <sup>2</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Broadlands, New Zealand <sup>3</sup>                                                                                                                                                                                                                                                  | Salton Sea geothermal field, California <sup>4</sup>                                                                                                                                                                               |  |

1) based, in part, on Heald et al., 1987; Taylor, 1987; Berger and Henley, 1989; Panteleyev, 1991; Rye et al., 1992; Sillitoe, 1993; Hedenquist et al., 2000; Izawa et al. 1990, 1993; and data reported for Canadian deposits and other examples cited in the text; 2) Nakamura et al., 1970; 3) Browne in Henley and Hedenquist, 1986; 4) Williams and McKibben, 1989, but analogy not complete.

Abbreviations: bn = bornite; cpy = chalcopyrite; cv = covellite; en = enargite; gn = galena; py = pyrite; sp = sphalerite; ss = sulphosalts.

Belt is host to Au deposits containing pyrophyllite, andalusite, topaz, and traces of diaspore (metamorphosed advanced argillic assemblage) marked by oxygen isotope depletion from meteoric-recharged hydrothermal systems (Klein and Criss, 1988), confirming an epithermal origin (see also Feiss et al., 1993).

Among Canadian examples, oxygen and hydrogen isotope measurements of vein quartz and of fluid inclusions, respectively, from the unmetamorphosed Au-Ag mineralized, low-sulphidation altered stockwork associated with Middle Proterozoic rhyolite dykes in the Mallery Lake area, Nunavut, confirm a meteoric origin and epithermal setting (Turner et al., 2001). Oxygen isotope data on rocks from the Hope Brook zone (B. Taylor and P. Stewart, unpub. data, 1990) suggest a magmatically dominated (high-temperature) origin rather than a shallow, meteoric (e.g. steam-heated) alteration system. Detailed geologic and mineralogical studies (Dubé et al., 1998) have corroborated this conclusion. Similarly, the association of Hg-Sb-As-Tl (e.g. Harris, 1989) and range in  $\delta^{34}\text{S}$  of pyrite (Cameron and Hattori, 1985) at the controversial Hemlo mine (Ontario), a disseminated Au deposit in the Precambrian Shield, might suggest a metamorphosed epithermal deposit. However, mineralized host rocks are not depleted in  $^{18}\text{O}$  (Kuhns, 1988), suggesting deeper level, magmatically dominant fluids. This is also supported by S isotope fractionations between sulphate-sulphide mineral pairs (Hattori and Cameron, 1986).

## Associated Mineral Deposit Types

Other deposit types that may be found broadly associated with epithermal deposits (i.e. within epithermal districts or camps) are those that share a common genetic link to magmatic centres (e.g. veins, skarns, and mantos; Sillitoe, 1993; Sillitoe and Thompson, 1998; Lang and Baker, 2001). Some vein and/or replacement deposits, typically of the intermediate sulphidation subtype (e.g. Silbak Premier, British Columbia, Table 1; Hedenquist et al., 2000), might be generally referred to as 'deep epithermal' or 'transitional' according to Panteleyev (1986, 1991). Because of the possibility of association, the locations of selected 'intrusion-related' or 'transitional' Au deposits in Canada have been included in Figure 1.

Often a 'barren gap' intervenes between the epithermal and 'deep epithermal' portions of magmatically heated geothermal systems. Close juxtaposition of epithermal vein and porphyry- or intrusion-related deposits may imply induced changes in the relative positions of meteoric geothermal systems and magmatic heat sources. Superposition of Au-bearing epithermal veins in the Coromandel Peninsula, New Zealand on slightly older Cu-Mo-Au porphyry deposits (e.g. Waihi deposit: Brathwaite and Faure, 2002), and superposition of a low-sulphidation subtype deposit on a porphyry Cu-type deposit in the Philippines (Acupan: Cooke and Bloom, 1990) are two examples. The extent of such superposition, or 'telescoping', may be tectonically and/or climatically controlled by rapid rates of uplift and high erosion, and volcanic sector collapse (Sillitoe, 1993; Müller et al., 2002a,b).

Deep epithermal veins ("transitional" deposits of Panteleyev, 1986) or replacement deposits associated with conventional epithermal deposits may comprise a compo-

nent of the genetic link between a degassing high-level magma and an overlying mineralized epithermal systems. The quartz-monzonite porphyry intrusion known beneath the Summitville, Colorado high-sulphidation magmatic-hydrothermal system is essentially coeval with Au mineralization and hydrothermal alteration (Bethke et al., 2005) and provides an example of the porphyry-epithermal linkage for high-sulphidation deposits. Intrusion-related vein deposits in the Sulphurets, Mt. Washington, and Zeballos camps, British Columbia, are possible Canadian examples (British Columbia Ministry of Energy, Mines, and Petroleum Resources, 1992; Margolis, 1993). Other, related hydrothermal deposits that may be associated with epithermal vein deposits, and represent the mesothermal counter part, include Au-bearing skarns (high-temperature, silica-replacement deposits; e.g., Hedley, British Columbia) and manto deposits (sulphide rich replacement; e.g., Ketz River, British Columbia) in carbonate rocks, and intrusion-adjacent deposits sometimes referred to collectively as such 'intrusion-related' deposits (e.g. Thompson et al., 1999; Lang and Baker, 2001).

Disseminated and vein Au deposits associated with alkaline intrusions (e.g. Howell Creek, Fernie, British Columbia: Brown and Cameron, 1999) have gained attention as a distinct type of intrusion-related Au deposit (e.g. Richards, 1995; Jensen and Barton, 2000; Robert, 2001). The Au-Te epithermal deposit(s) at Cripple Creek, Colorado, represent a classic association with alkaline (diatreme) magmatic rocks; no extrusive rocks are present at this level of erosion (e.g. Kelley et al., 1998).

Hot-spring deposits, including siliceous sinters, steam-heated alteration zones, and brecciated root zones (e.g. Cinola, British Columbia: Christie, 1989; see also Izawa et al., 1993), cap many modern geothermal systems, and may be associated with either low- or high-sulphidation epithermal deposits. Their formation at the Earth's surface makes them very susceptible to erosion, however. Modern and recent deposits are most common, and examples are found worldwide, including Japan, Indonesia, New Zealand (e.g. Champagne Pool, Wairakai), Nevada (Round Mountain: Sander and Einaudi, 1990), and California (McLaughlin: Sherlock, 2005). Older, Jurassic, sinters, and related Au-Ag epithermal deposits are also known from Patagonia, Argentina (Schalamuk et al., 1997). Gold grades are typically variable and subeconomic, but the presence of Au, along with Hg, Sb, As, S, and Tl, may suggest a mineralized root zone, or deeper epithermal deposit.

Volcanogenic massive sulphide (VMS) deposits that form at or near the seafloor from submarine hot springs and sub-seafloor geothermal systems are epithermal deposits in the broad sense (e.g. Sillitoe et al., 1996). Gold-bearing VMS deposits (e.g. Horne mine, Noranda: Dubé et al., 2007; Eskay Creek 21B, British Columbia: Roth et al., 1999) are recognized as a type of VMS deposit (Dubé et al., 2007), and both high-sulphidation and low-sulphidation variants have been recognized (Sillitoe et al., 1996). Similarly, island arc settings may also host submarine calderas and epithermal deposits (e.g. Pueblo Viejo high-sulphidation subtype: cf. Kesler et al., 2005; Sillitoe et al., 2006; Milos, Greece: Naden et al., 2005). Indeed, many of the same processes

regarding origins and causes of metal deposition and enrichment associated with continental epithermal deposits apply to these shallow marine settings. Comparison of S isotope geochemistry between adjacent subaerial and submarine mineralized systems in Papua New Guinea (Gemmell et al., 2004) offers further supportive evidence. Thus, the submarine environment should not be ignored with regard to epithermal deposits, despite the fact that some features (steam-heated alteration caps, dominance of meteoric waters, etc) familiar among subaerial epithermal and hot-spring deposits are necessarily absent.

### Economic Characteristics of Epithermal Gold Deposits

#### Summary of Economic Characteristics

Gold ( $\pm$ Ag) is the principal commodity of epithermal Au deposits, occurring usually as native Au, or in electrum alloyed with Ag. It may also occur in tellurides, or as inclusions in sulphides. Copper and the other base metals, Pb and Zn, may also occur with Au, especially in transitional epithermal deposits with high Ag grades. Indeed, the common presence of enargite has led to the term enargite-Au deposits for some high-sulphidation subtype deposits (Ashley, 1982).

Epithermal (vein-) deposits, compared to the low-grade, bulk-tonnage porphyry deposits or the 'Carlin-type' deposits, are typically small in size (e.g.  $10^6$  to  $10^8$  tonnes of ore; high-sulphidation deposits tend to be smaller than low-sulphidation deposits) and, consequently, have a short mining life. However, epithermal Au deposits can reach high grades, a few to several tens of g/t, or more in exceptional cases (e.g. 70 g/t, Hishikari, Japan; to ~200 g/t, El Indio, Chile; Table 1).

Epithermal Au deposits represent a minor proportion, typically a few percent, of the total Au (reserves + production) in Canada. For example, epithermal deposits yielded an average annual production of 2725 kg/year, or about 2.7% of the total annual Au produced in Canada from 1985 to 1987. Owing largely to occurrence tending to favour geologically younger terrane, epithermal Au contributed relatively more (as much as 24%) of the total Au produced in British Columbia and the Yukon during the same period.

#### Grade and Tonnage Characteristics

The sizes (in  $10^6$  tonnes) of the principal Canadian epithermal Au vein deposits and selected 'type' deposits elsewhere are listed in Table 1, and plotted versus Au grade (g/t) by class of deposit in Figure 3. The mean grade and tonnage of several classic examples of non-Canadian deposits (low-sulphidation: Creede, Colorado, and Hishikari, Japan; high-sulphidation: Summitville, Colorado; average Au-bearing porphyry deposit; and average Carlin-type deposit, Nevada) are plotted for comparison. The estimated sizes (ca. 0.05 to 42 Mt of ore) give an order of magnitude basis for comparison; definition of size depends on cut-off grades and economics. Ore comprises disseminated Au in silicified and/or finely veined rocks in the Cinola deposit, British Columbia, and in areas of the Sulphurets district, British Columbia. Here, grades are typically lower, but tonnages larger, than in other, vein-type, epithermal deposits (Table 1). Based on a reported grade of 2.45 g/t and 23.80 Mt of ore,

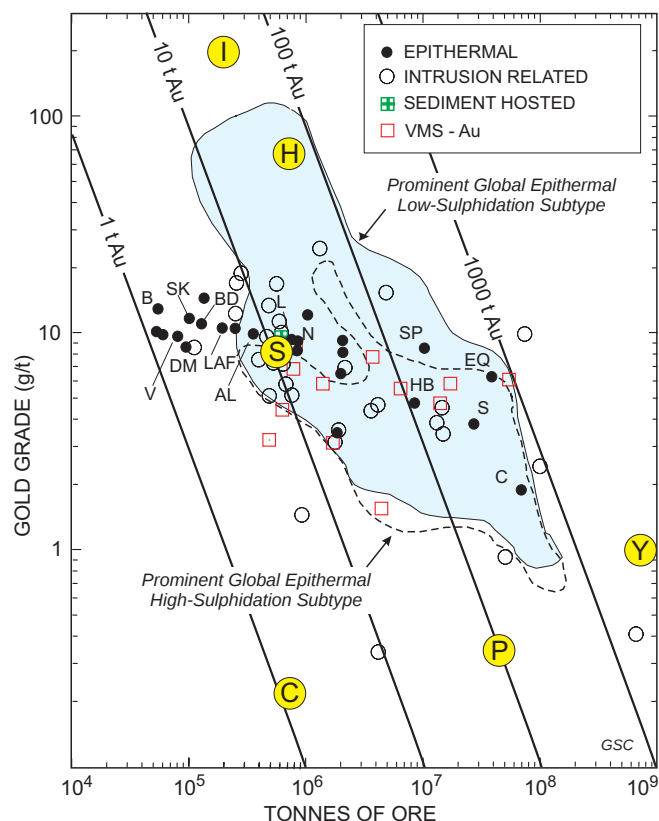


FIGURE 3. Plot of Au grade (g/t) versus tonnage (economic, or reserves+production) for selected Canadian epithermal Au deposits and prominent examples elsewhere in the world, classified by subtype as referred to in the text. Canadian epithermal deposits (filled circles; see Table 1) include AL = Al; B = Baker; BD = Blackdome; C = Cinola; DM = Dusty Mac; EQ = Equity Silver; HB = Hope Brook; L = Lawyers; LAF = Laforma; N = Mt. Nansen; SK = Mt. Skukum; SP = Silbak Premier; S = Sulphurets camp (Brucejack Lake, Sulphuret, West Zone deposits); and V = Venus. Hydrothermal vein deposits of a possible 'transitional' or 'deep epithermal' deposits are represented by open circles, sediment-hosted deposits by a green square with cross, and Au-bearing VMS deposits ('marine epithermal') by open red squares (see Appendix 1 in Dubé et al., 2007). The median grades and tonnages for several comparable types of deposits (yellow-filled circles) from Cox and Singer (1986) include porphyry Cu-Au [P]; low-sulphidation Creede-type [C]; intermediate sulphidation: polymetallic vein deposits associated with felsic intrusions [M]; and high-sulphidation: Summitville deposit [S]; and Lawyers deposit, Toadoggon River district, British Columbia [L] is similar to the 'Comstock-type', Nevada (not plotted) of Cox and Singer, 1986]. Median values for the low-sulphidation Hishikari, Japan vein deposit [H], and for the high-sulphidation El Indio, Chile, deposit [I] are from Hedenquist et al. (2000). Fields for prominent low-sulphidation (blue shading) and high-sulphidation (dashed line) epithermal Au deposits worldwide (global) are based on data in Hedenquist et al. (1996; 2000).

the Cinola deposit is potentially the second largest epithermal Au deposit in Canada. For vein-style epithermal deposits, the Au grades of Canadian examples (most ~2.5-25 g/t) are similar to those of a majority of 'mesothermal' quartz-carbonate deposits (see Gosselin and Dubé, 2005a-d), but of generally smaller size, and are distinguished from the latter by higher Ag: Au ratios (>1:1).

Canadian epithermal Au deposits are comparable in size and grade to many deposits found in the major epithermal terranes of the world, as illustrated in Figure 3. The largest epithermal deposits (in tonnes of ore) and the richest deposits (in g/t) are found outside of Canada. Fields for prominent low-sulphidation subtype epithermal Au deposits

and for high-sulphidation subtype epithermal Au deposits (from data in Hedenquist et al., 1996, 2000) overlap, but suggest that high-sulphidation subtype deposits tend to be comparable in size and grade to the smaller of the low-sulphidation subtype deposits. Several non-Canadian epithermal deposits selected by subtype to reflect the global range of grade and tonnage are plotted together with Canadian deposits in Figure 3.

### Exploration Properties of Epithermal Gold Deposits

#### *Physical Properties*

The mineralogy, textural features, host rocks, morphology, and selected chemical properties found typically in epithermal Au deposits are summarized in Table 2. Key features are emphasized below.

#### Mineralogy

Quartz is the predominant gangue mineral in all epithermal Au deposits, whereas distinctive ore and gangue minerals characterize high-sulphidation and low-sulphidation deposit subtypes. Mineralogical zoning around veins or replacement zones may be present in both subtypes, recording chemical and/or thermal gradients. Both subtypes of deposits can contain very fine-grained Au and gangue mineral assemblages, especially in hot-spring and steam-heated environments that form above boiling hydrothermal systems (Henley and Ellis, 1983).

In high-sulphidation subtype deposits, native Au and electrum are typically associated with pyrite+enargite+covelite±bornite±chalcocite. In addition to sulphosalts and base metal sulphides, tellurides and bismuthinite are present in some deposits. Total sulphide contents are generally higher in high-sulphidation than low-sulphidation subtype deposits, but high sulphide contents may also characterize transitional polymetallic low-sulphidation deposits (e.g. Silbak Premier, British Columbia). Where base metals are present in high-sulphidation deposits, the Cu abundance can vary significantly (<0.1-5%; Sillitoe, 1993), and typically dominate that of Zn. Principal gangue minerals include quartz ('vuggy silica'), alunite, barite (especially associated with Au), and, in some deposits, S; manganese minerals and fluorite are rare. Calcite is not characteristic of high-sulphidation subtype deposits due to the high acidity of the hydrothermal fluids.

Native Au and electrum occur in low-sulphidation subtype vein deposits that often contain only a few percent or less of sulphides (usually pyrite; e.g., Blackdome, British Columbia). In deposits in which sulphide minerals are abundant (e.g. Venus; Silbak-Premier: sulphide-rich stage), sulphides commonly include chalcopyrite, tetrahedrite, galena, sphalerite, and arsenopyrite in addition to pyrite. The principal gangue minerals include calcite, chlorite, adularia, barite, rhodochrosite, fluorite, and sericite.

In sediment-hosted low-sulphidation deposits, the characteristic assemblage of gangue minerals commonly includes cinnabar, orpiment-realgar, and stibnite, in addition to jasperoid, quartz, dolomite, and calcite. Chalcedonic quartz veins and jasperoid are typically associated with ore, whereas calcite veins are often more common further from ore, or are paragenetically late. In siliceous sinter associated with hot-spring deposits, sulphate minerals, clays, and minor

pyrite constitute the typical gangue assemblage; vertical zoning of alteration mineral assemblages is characteristic.

In some deposits hosted by volcanoclastic rocks (e.g. McDermitt, Nevada), micrometre-size Au grains are typical, although visible (recrystallized) native Au may occur in oxidized portions of some deposits. Gold can occur coating sulphides and/or encapsulated in quartz in silicified rocks, accompanied by Hg-, Sb-, and As-bearing sulphides. At Cinola, British Columbia, a rare example in Canada (Christie, 1989; see also Poulsen, 1996), Au is most abundant in the subsurface silicified sediments and hydrothermal breccias. Inclusion of sediment-derived hydrocarbons may occur during vein formation in sedimentary rocks, or deposits within hydrothermal systems encompassing sedimentary rocks (e.g. Owen Lake, British Columbia: Thomson et al., 1992).

#### Textures

Vuggy silica has a porous texture formed by removal of minerals, particularly feldspars during reaction with very acidic fluids and concentration of residual silica (e.g. Summitville, Colorado: Stoffregen, 1987). Massive, quartz-rich zones may result from further silicification (i.e. by addition of silica). Examples include alteration zones at Mt. Skukum, Yukon (alunite cap zone: Love, 1989) and at the Al deposit (Toodoggone River, British Columbia: Diakow et al., 1993). In high-sulphidation subtype deposits, coarse-grained alunite is characteristic, whereas alunite from steam-heated zones (high-sulphidation subtype caps to epithermal systems), and from supergene weathering of sulphide deposits, is typically very fine grained to microcrystalline.

Lamellar or platy ('angel wing') calcite, in some cases pseudomorphically replaced by silica (e.g. Mt. Skukum, Yukon), is of particular significance because it forms in boiling zones in low-sulphidation subtype systems (e.g. de Ronde and Blattner, 1988; Simmons and Christenson, 1994). Rhombic adularia has been similarly associated with boiling (Keith and Muffler, 1978; Dong and Morrison, 1995).

Unique to (unmetamorphosed) hot-spring deposits, are non-horizontal laminated or 'bedded' lenses that may contain textures formed by silica fossilization of plant matter (root casts, etc.), and vertical crystallization textures and structures.

#### Dimensions

High-sulphidation deposits of magmatic hydrothermal origin (e.g. Rye et al., 1992) are typically of smaller dimension than low-sulphidation subtype deposits, and are found in close proximity to, and often topographically above, a related source of magmatic heat and volatiles. Altered rocks of the Summitville, Colorado, deposit, for example, crop out over an area of 1.5 by 1.0 km (Heald et al., 1987). Shallow, steam-heated environments, in contrast, may produce widespread altered areas, typically (but not always) barren; bulk-tonnage mining of these zones may be possible if they are mineralized. For example, mineralized areas altered to quartz+clay+alunite (+barite+dickite) at the Al deposit, Toodoggone River area, British Columbia, measure about 250 m by as much as 1.5 km (Diakow et al., 1993). Fault-controlled, quartz-(kaolinite)-alunite alteration zones meas-

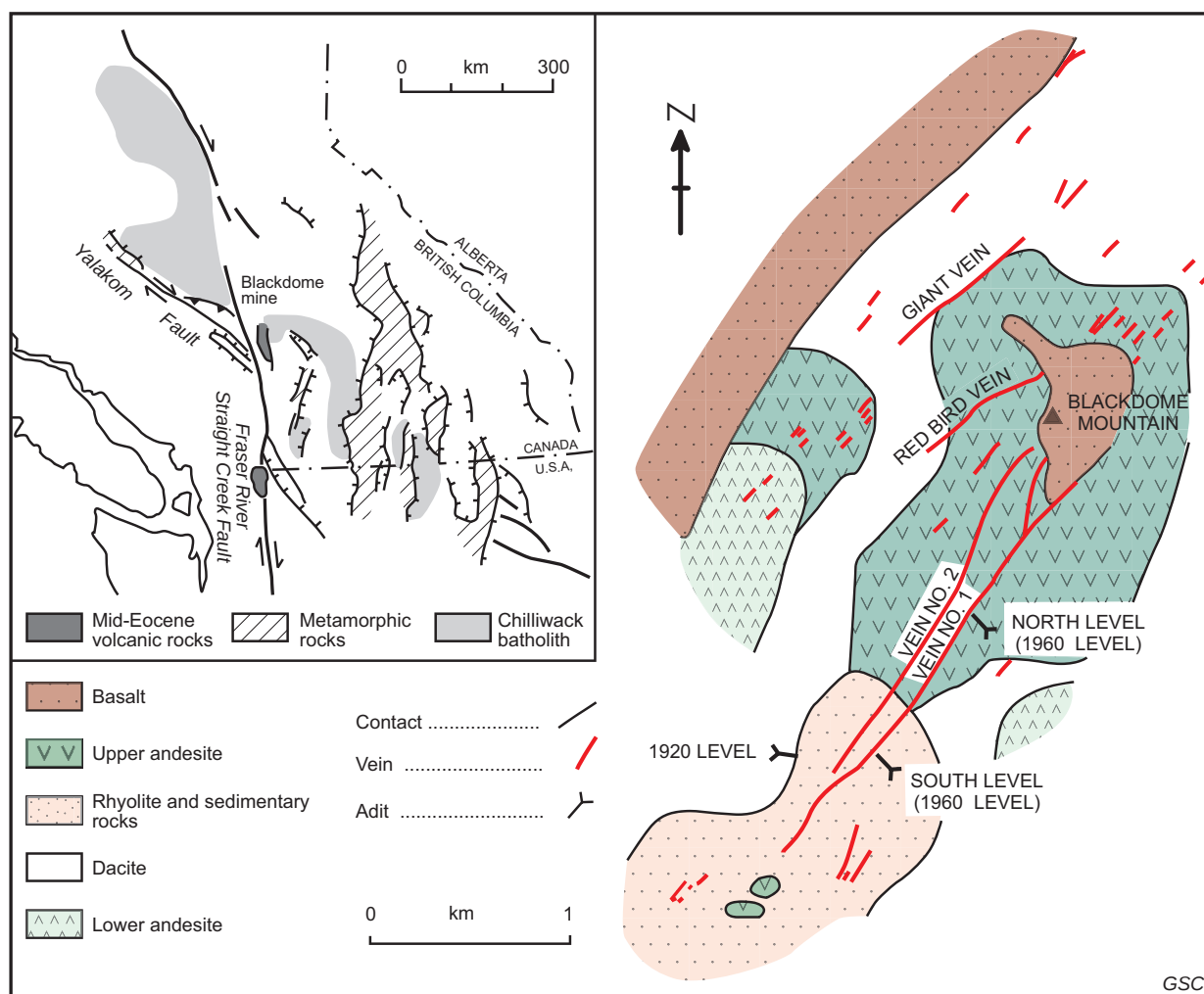


FIGURE 4. Geological map illustrating setting of the epithermal Au vein deposit at the Blackdome mine, British Columbia (from Taylor, 1996; data from D. Rennie, unpub. rep., 1987). Inset map illustrates the regional tectonic setting of the Blackdome mine area (red square), between the Yalakom (55-45 Ma) and younger Fraser River Straight Creek (40-35 Ma) strike-slip fault (Coleman and Parrish, 1990; R.R. Parrish, pers. comm., 1991).

uring roughly 200 by 250 m occur topographically above the Mt. Skukum deposit, in an area partially removed by erosion (McDonald, 1987). Similarly altered prospective areas occur in folded Neoproterozoic (Avalonian) rocks in the Burin Peninsula, Newfoundland affected by advanced argillic alteration (pyrophyllite-alunite-specularite; e.g., O'Brien et al., 1999). Two of these measure approximately 125 by 225 m (Hickey's Pond prospect) and 4700 m x 4 km (Stewart prospect), although evidence of similar alteration is present over a length of approximately 100 km. The Avalonian Carolina slate belt hosts high-sulphidation subtype gold deposits (abandon mines) of similar age, alteration style, and dimension (c.f. Klein and Criss, 1988; O'Brien et al., 1999).

Low-sulphidation subtype deposits in some cases cover larger areas than typical of high-sulphidation deposits, even though alteration mineral assemblages are restricted to generally narrow zones enclosing veins and breccias. At the Blackdome mine, British Columbia (Fig. 4), quartz veins as much as 0.7 m thick and 2200 m long, are contained within an area approximately 2 by 5 km. Veins comprising the Lawyers deposit and the Baker mine in the Toodoggone district, British Columbia, are commonly 2 to 7 m wide and as much as several hundred metres in length. Veins and breccia

zones as wide as 40 m and as long as 1200 m comprise the Main zone of the Silbak-Premier deposit in British Columbia (McDonald, 1990). Elsewhere, mineralized veins in low-sulphidation subtype epithermal deposits have been mined for a strike length of more than 5 km at Creede, Colorado (Heald et al., 1987), and occur for a distance of about 2 km at the high-grade (e.g. 70 g/t) Hishikari mine, Japan (Izawa et al., 1990). Alteration zones around the veins of the Hishikari deposit have been mapped in an area measuring as much as 2 km wide by more than 3 km long (Izawa et al., 1990).

Hot-spring deposits comprising surface lenses or aprons of silica (siliceous sinter), may be several hundred metres in diameter, but only metres to tens of metres in thickness. Discordant hydrothermal conduits beneath these deposits may extend over a hundred or more metres in the vertical dimension, and resemble funnel-like forms in section, decreasing from perhaps many tens of metres to a few metres with depth (e.g. Christie, 1989).

#### Morphology

The morphology of epithermal vein-style deposits can be quite variable. Deposits may consist of roughly tabular lodes controlled by the geometry of the principal faults they

occupy (e.g. Cirque vein, Mt. Skukum; Fig. 5; Table 1), or comprise a host of interrelated fracture fillings in stockwork, breccia, lesser fractures, or, when formed by replacement of rock or void space, they may take on the morphology of the lithologic unit or body of porous rock (e.g. irregular breccia pipes and lenses) replaced. Volumes of rock mineralized by replacement may be discordant and irregular, or concordant and tabular, depending on the nature of porosity, permeability, and water-rock interaction. In deposits of very near-surface origin (e.g. Cinola), an upward enlargement of the volume of altered and mineralized rocks may be found centred about the hydrothermal conduits. Hot-spring deposits tend to comprise subhorizontal aprons or lenses of sinter about their upflow zones and subhorizontal replacement zones in the shallow subsurface. Phreatic eruptions produce discordant zones of breccia-like deposits; clasts may be partially rounded (e.g. Izawa et al., 1990).

Brecciation of previously emplaced veins (e.g. Mt. Skukum, Yukon) can form permeable zones along irregularities in fault planes: vertically plunging ore zones in faults with strike-slip motion and horizontal ore zones in dip-slip faults. Topographic (i.e. paleosurface) control of boiling by hydrostatic pressure can also result in horizontal or subhorizontal mineralized zones, limiting the vertical distribution of ore (as suggested in Fig. 5; Cirque vein, Mt. Skukum, Yukon). The distribution of high-sulphidation alteration in steam-heated settings (possibly in the Toodoggone River camp, British Columbia) may also reflect a topographic control of the paleo-water table.

### Host Rocks

Nearly any rock type, even metamorphic rocks, may host epithermal Au deposits, although volcanic, volcanoclastic, and sedimentary rocks tend to be more common. Typically, epithermal deposits are younger than their enclosing rocks, except in the cases where deposits form in active volcanic settings and hot springs. Here, the host rocks and epithermal deposits can be essentially synchronous with spatially associated intrusive or extrusive rocks, within the uncertainty of the determined ages in some cases (e.g. high-sulphidation Summitville deposit, Colorado: Bethke et al., 2005; low-sulphidation El Peñon deposit, Northern Chile: Arancibia et al., 2006).

### Chemical Properties

#### Ore Chemistry

Gold:silver ratios of epithermal Au deposits may vary widely both between and within deposits from 0.5 for the high-sulphidation type Kasuga deposit, Japan (Hedenquist et al., 1994), for example, to  $>>500$  in the Cerro Rico de Potosi deposit, Peru (Erickson and Cunningham, 1993). Differing

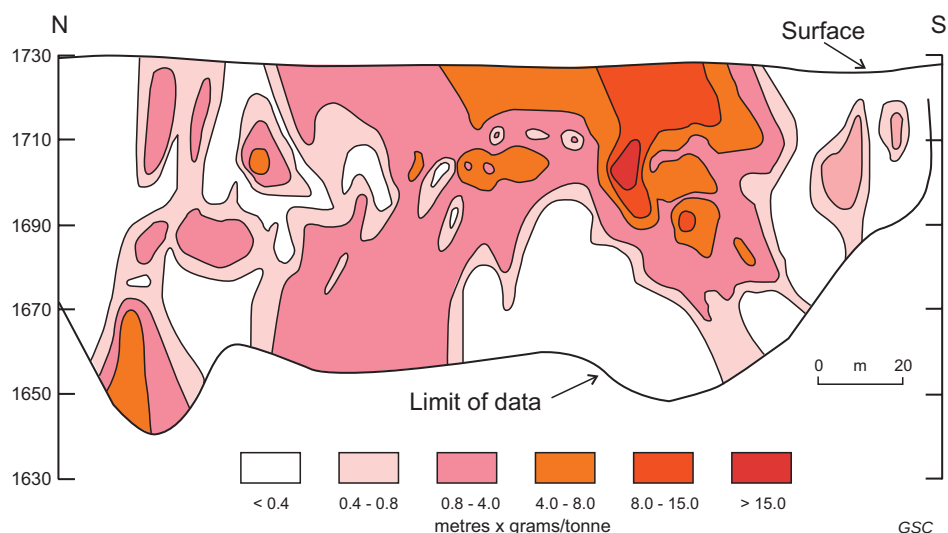


FIGURE 5. Longitudinal section of the Cirque vein, Mt. Skukum (from Taylor, 1996, modified after McDonald, 1987) illustrating distribution of Au (thickness x grade).

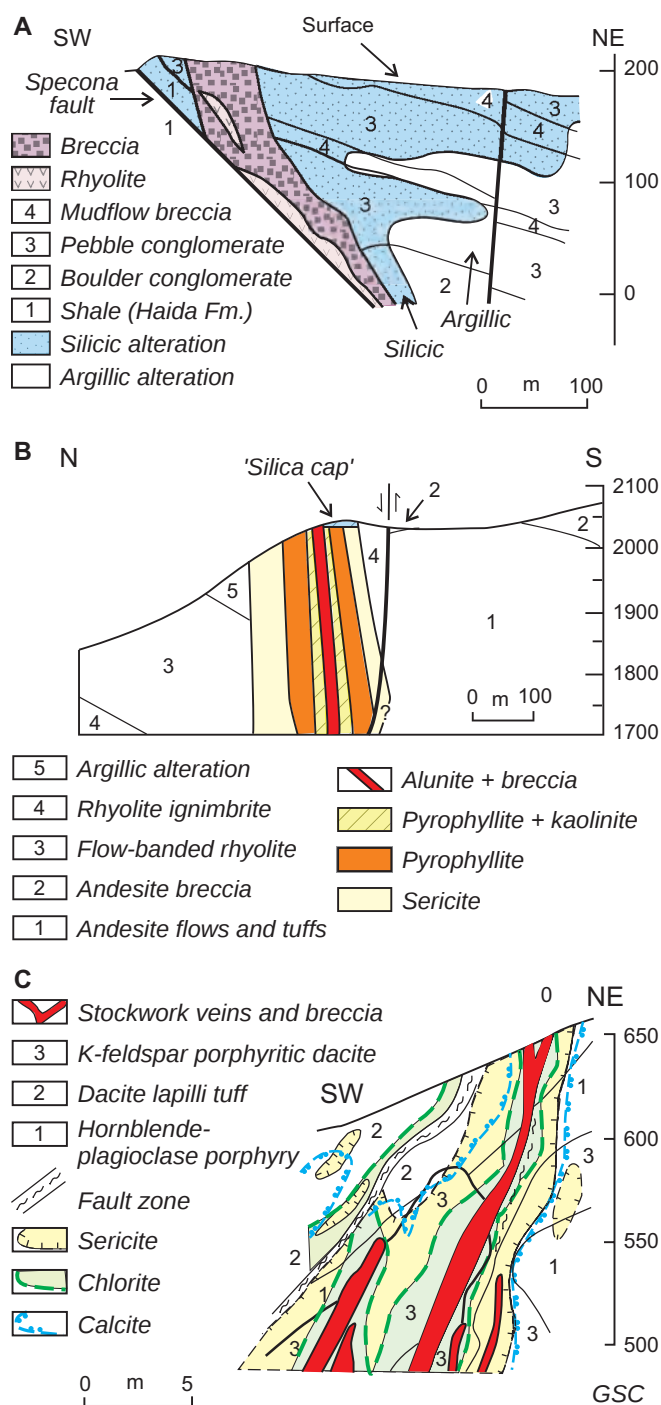
magmatic metal budgets (Sillitoe, 1993) and depths of formation (Hayba et al., 1985) have been suggested to influence this ratio. At the Lawyers deposit, Toodoggone River district, British Columbia, the Ag:Au ratio varies northward in the deposit, from less than 20 to more than 80 (average = 46.7; Table 1), and higher ratios are also found at deeper levels of the deposit (Vulimiri et al., 1986). Typically, Ag:Au ratios for epithermal deposits, though variable, tend to be higher in low-sulphidation subtype deposits than in high-sulphidation subtype deposits (Table 1). The deep epithermal (mesothermal) Equity Silver deposit, British Columbia (e.g. Cyr et al., 1984; Wojdak and Sinclair, 1984) has the highest Ag:Au ratio (approximately 128; Table 1) among Canadian epithermal deposits.

High precious metal/base metal ratios in hot-spring deposits (and steam-heated zones in general) are thought to be characteristic. Buchanan (1981) suggested that base metals precipitate in deeper, more saline, liquid-dominated portions of the system, whereas deposition of Au occurs in an upper, gas-rich, or boiling portion of the geothermal system, resulting in the observed metal separation.

Whereas base metals may accompany Au ( $\pm$ Ag) in variable amounts in intrusion-related or transitional deposits, more volatile elements commonly occur with Au ( $\pm$ Ag) in shallower epithermal and hot-spring environments. These elements characteristically include Hg, Sb, Tl, As, and native S.

### Alteration Mineralogy and Chemistry

Examples of alteration mineral zoning and its relationship to lithology are illustrated for portions of three Canadian deposits in Figure 6A-C (sediment-hosted low-sulphidation subtype: Cinola, British Columbia; volcanic-hosted low- to intermediate-sulphidation subtype: Silbak-Premier, British Columbia; Fig. 5C), and rhyolite/andesite-hosted high-sulphidation alteration topographically above the low-sulphidation subtype (Mt. Skukum deposit, Yukon). Alteration was, in each case, structurally controlled, cross-cutting the host rocks. Symmetrical zoning developed about some veins (e.g.



**FIGURE 6.** Geological cross-sections of representative Canadian epithermal deposits illustrating alteration mineral zoning and selected features (from Taylor, 1996). **(A)** Cinola sedimentary-hosted Au deposit (after Christie, 1989; low-sulphidation subtype), also illustrating localization of both magma (interpreted from faulted dyke) and hydrothermal fluids by the Specona fault, and the control exerted by primary lithological permeability on the distribution of zones of silicification and argillic alteration. **(B)** Cross-section through a portion of a principal normal fault in the Mt. Skukum area (after Love, 1989; low-sulphidation subtype, volcanic host) illustrating the distribution of associated alunite+silica, and advanced argillic alteration mineral assemblages. Supergene alteration has been superposed on quartz-(kaolinite)-alunite alteration zones. **(C)** Cross-section through a portion of the Silbak-Premier deposit (intermediate sulphidation; after McDonald, 1990) illustrates hydrothermal propylitic, sericitic, and potassic alteration mineral assemblages in relation to fault-controlled vein stockwork and breccia, and to porphyritic dacite.

Mt. Skukum, Yukon), but was markedly asymmetrical in other cases (e.g. Cinola, British Columbia).

In both high-sulphidation and low-sulphidation deposit subtypes, hydrothermal alteration mineral assemblages are commonly regularly zoned about vein- or breccia-filled fluid conduits, but may be less regularly zoned in near-surface environments, or where permeable rocks have been replaced. Characteristic alteration mineral assemblages in both deposit subtypes can give way to propylitically altered rocks containing quartz+chlorite+albite+carbonate±sericite, epidote, and pyrite. The distribution and formation of the earlier formed propylitic mineral assemblages generally bears no obvious direct relationship to ore-related alteration mineral assemblages.

Altered rocks in low-sulphidation deposits generally comprise two mineralogical zones: (1) inner zone of silicification (replacement of wall rocks by quartz or chalcedonic silica); and (2) outer zone of potassic-sericitic (phyllic) alteration (quartz+K-feldspar and/or sericite, or sericite and illite-smectite). Adularia is the typical K-feldspar, but its prominence varies greatly; it may be absent altogether. Chlorite and carbonate are present in many deposits, especially in wall rocks of intermediate composition, and in some cases (e.g. Shasta deposit, Toodoggone River, British Columbia: Thiersch and Williams-Jones, 1990; Silbak-Premier: McDonald, 1990) chloritic alteration accompanied the potassic alteration and silicification. Argillic alteration (kaolinite and smectite) occurs still farther from the vein. In some deposits (e.g. Cinola: Christie, 1989), argillic alteration predates silicification, giving evidence of the waxing and waning of hydrothermal systems. Argillic mineral assemblages are commonly superposed on the above, or form in higher level alteration zones (e.g. Toodoggone River area, British Columbia: Diakow et al., 1993), where adularia is replaced by kaolinite; smectite may occur furthest from the veins.

Silicified rocks are common in epithermal deposits, as is quartz gangue in veins. For example, in both the volcanic-hosted Blackdome deposit, British Columbia, and sedimentary-hosted Cinola deposit, irregularly silicified and mineralized wall rocks are common adjacent to faults and fractures. Silicified and decarbonated host rocks characterize Carlin-type Au deposits in Nevada (e.g. Bagby and Berger, 1986). The silicification of wall rocks (and the distribution of ore) was apparently controlled by available primary permeability of bedding planes or rock fabric. Secondary permeability can also be produced by physical and chemical processes involving the hydrothermal fluids themselves. The sudden release of pressure on hydrothermal fluid (e.g. by faulting) can cause brecciation, creating pore space permeability (e.g. Cinola, British Columbia, breccia zone in Fig. 6A). This can occur in geothermal systems within several hundred metres of the Earth's surface (e.g. Hedenquist and Henley, 1985). Dissolution of carbonate upon reaction between hydrothermal fluids and wall rocks also can produce secondary permeability.

Based on the nature of silicification, Bagby and Berger (1986) distinguished two types of sediment-hosted deposits: jasperoidal- and Carlin-type; the latter is no longer considered a subtype of epithermal Au deposits. Jasperoidal deposits may occur in clastic sedimentary rocks, where sili-

cification is characterized by quartz veins (commonly) and/or replacement (e.g. Cinola, British Columbia). Other effects of alteration are otherwise similar, and include decarbonation (where rocks originally contained carbonate) and argillization. Alteration minerals include alunite, quartz, calcite, illite, cinnabar, orpiment, realgar, stilbite, pyrite, pyrrhotite, marcasite, and arsenopyrite.

Advanced argillic alteration mineral assemblages that characterize high-sulphidation deposits include quartz+kaolinite+alunite+dickite+pyrite in and adjacent to veins or zones of replacement in the magmatic-hydrothermal environment. Pyrophyllite occurs in place of kaolinite at the higher temperatures and pressures of deeper deposits. In some outer zones (e.g. alunite 'cap'; Mt. Skukum), argillic (smectite)±sericite mineral assemblages may occur (Fig. 6B). These alteration minerals indicate a very low pH hydrothermal environment (possibly below even that for alunite stability; Stoffregen, 1987) of high oxidation state (hematite and sulphate are stable). Zones of silica replacement and 'vuggy silica' are characteristic, and carbonates are absent. Topaz and tourmaline in high-temperature zones indicate the presence of F and B in the acidic hydrothermal fluids.

Acid-sulphate (high-sulphidation) type alteration fluids form by the dissolution of large amounts of magmatic SO<sub>2</sub> in high-temperature hydrothermal systems, and also by reaction of host rocks with steam-heated meteoric waters acidified by oxidation of H<sub>2</sub>S (probably of magmatic origin: e.g., Rye et al., 1992; Bethke et al., 2005), or by dissolution of CO<sub>2</sub>. Two contemporaneous fluids are typically found to have been significant in epithermal Au deposits, and particularly in the high-sulphidation subtype (e.g. Summitville, Colorado: Bethke et al., 2005; Pierina, Peru: Fifarek and Rye, 2005). These are a saline fluid (typically ~10–40 wt.% NaCleq) found often in the deeper portion of the hydrothermal system, associated with mineralized zones, and a low-density (<10% NaCleq) fluid more commonly found in the upper part of the hydrothermal system. The more saline fluids are often interpreted to have evolved from magmatic fluids and to have transported the metals to meteoric-water dominated geothermal system. In rare situations where recharge of surficial waters is limited (e.g. <10 Ma, Andes) magmatic waters may dominate throughout (e.g. Pascua-Lama, Chile: Deyell et al., 2005). Lower acidity, highly saline fluids are thought responsible for intermediate sulphidation deposits typically rich in base metal and Fe sulphide minerals (Hedenquist et al., 2000).

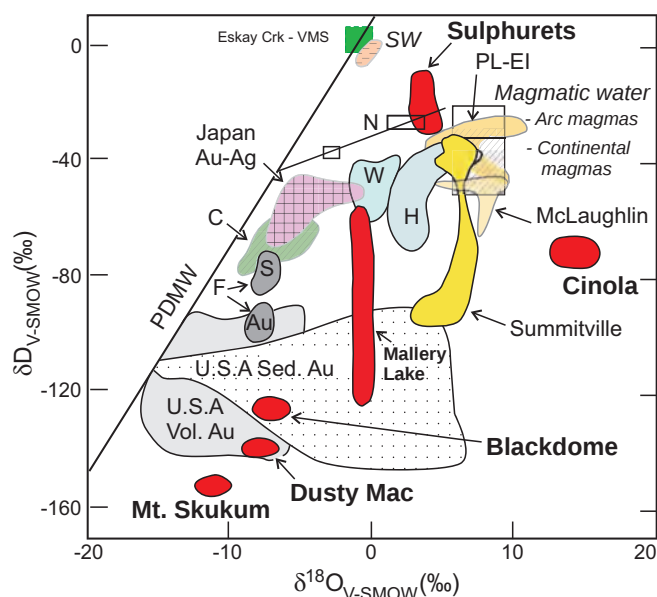
Fluids attributed to low-sulphidation hydrothermal systems are typically less saline than those in high-sulphidation systems, although fluids of two different salinities are also common: a deeper fluid of perhaps approximately 10 to 20 wt.% NaCleq is responsible for metal transport, along with a shallower, dilute fluid (<1 wt.% NaCleq). Stable isotope data, along with other geochemical attributes, indicate that the two fluids evolved from a single, low to intermediate salinity fluid via boiling (e.g. Waihi, New Zealand: Brathwaite and Faure, 2002). The primary fluids in low-sulphidation subtype deposits are commonly inferred to have largely evolved from meteoric rather than magmatic water,

or comprise some mixture of the two (e.g. Hishikari, Japan: Faure et al., 2002).

Distinguishing steam-heated environments, localized above deeper, boiling hydrothermal systems (Henley and Ellis, 1983), whether of low-sulphidation or high-sulphidation subtype, from shallow magmatic hydrothermal environments is not always straightforward. Steam-heated, high-sulphidation alteration zones may occur as 'blankets' above low-sulphidation deposits (e.g. Sulphurets, B.C.; Margolis, 1993) and also at the top of high-sulphidation systems, and may or may not directly overlie mineral deposits (Henley, 1985). Alunite is a characteristic mineral of hypogene high-sulphidation alteration, but may also occur in steam-heated environments, above either low- or high-sulphidation systems. In addition, alunite may form during supergene weathering of sulphide deposits. Distinguishing the alunite formed in different environments may be aided by texture: hypogene alunite is typically coarse-grained; supergene alunite is typically fine-grained and poorly crystallized; the presence of halloysite, iron oxides, jarosite, possible supergene enrichment, and subhorizontal mineral zoning characterize the supergene nature of the alteration. In metamorphosed deposits, alunite texture is a less reliable criterion, and low-temperature minerals usually no longer exist. Stable isotope studies, however, can distinguish supergene alunite, steam-heated alunite, and magmatic-hydrothermal hypogene alunite (Rye et al., 1992; Rye, 2005).

Stable isotope techniques offer a particularly powerful tool to map and decipher paleo-hydrothermal systems represented by altered and mineralized rocks, and to guide exploration, even in highly metamorphosed terrane. Oxygen and hydrogen isotope, and fluid inclusion studies have thus far indicated that Au precipitating hydrothermal fluids in epithermal deposits typically comprise mixtures of low-salinity, meteoric waters and more saline waters. The saline waters can be either magmatic water or evolved waters formed by reaction of hydrothermal fluids with host rocks, by boiling and/or by mixing of magmatic volatiles and other evolved fluids. Saline fluids have been shown to be especially important in the transport of base metals. Volatile components (e.g. metals, F, Cl, CO<sub>2</sub>, SO<sub>2</sub>, etc.) may be added to geothermal systems by subsurface magmatic degassing, forming fluids with magmatic isotopic characteristics that are common to high-sulphidation systems. Magmatic water and volatiles tend to constitute a minor, if even detectable, component of fluids in low-sulphidation subtype deposits (except for C and S in some cases).

The hydrothermal fluids responsible for alteration in selected Canadian and non-Canadian deposits, including fields for several groups of deposits, are plotted in a  $\delta D$  versus  $\delta^{18}O$  diagram in Figure 7. The fluids responsible for alteration and mineralization largely represent altered or 'evolved' meteoric waters whose isotopic compositions have been shifted to higher <sup>18</sup>O/<sup>16</sup>O and D/H (deuterium-to-hydrogen) ratios than those of pure local meteoric waters (compare with present day meteoric water, 'PDMW', Fig. 7). Such isotopic alteration or evolution of the fluids occurs during chemical, isotopic, and mineralogical hydrothermal alteration of the host rocks, and is denoted by curved reaction paths in Figure 7 (e.g. field of fluids for the Summitville



**FIGURE 7.** Plot of  $\delta^{18}\text{O}$  versus  $\delta\text{D}$  for present day meteoric waters and for waters in equilibrium with gangue minerals in selected epithermal Au deposits; Canadian examples are shown in red (modified from Taylor, 1996, with additions). This diagram illustrates the origin and oxygen isotope enrichment of meteoric waters in many epithermal vein systems. Abbreviations are for the Finlandia vein [F], Colqui district, Peru (S = sulphide stage; Au = precious metal stage); PDMW = present day meteoric water; SW = seawater (note similar composition for fluids in the Eskay Creek Au deposit; Sherlock et al., 1999); U.S.A. SED. Au = sedimentary rock-hosted Au in the United States; U.S.A. Vol. Au = volcanic rock-hosted Au in the United States. Magmatic water composition defined by Taylor (1987, 1992). Sources of data for Canadian deposits: Taylor (1987); Blackdome: Vivian et al. (1987); Cinola: B. Taylor and A. Christie (unpub. data, 1991); Dusty Mac: Zhang et al. (1989); Mallery Lake: Turner et al. (2001); Sulphurets: Margolis (1993), and Mt. Skukum: McDonald (1987) and B. Taylor (unpub. data, 1991). Sources for non-Canadian deposits: [H] Hishikari, Japan: Faure et al. (2002); [W] Waihi, New Zealand: Braithwaite and Faure (2002); others, including Creede, Colorado [C], Finlandia vein Colqui, Peru [F: Au- and S-rich stages] as cited in Taylor (1987). Mixing with meteoric waters that evolved by water/rock reaction is indicated by the Summitville field of waters. Mixing of magmatic fluids and local meteoric water in the Nansatsu deposit, Japan [N] is shown by the straight dashed mixing line.

deposit). The mixing of meteoric waters (PDMW) with either modified fluids or magmatic fluids is indicated by straight lines (e.g. such indicated for the Nansatsu deposit, 'N'). Variations of  $\delta\text{D}$  or  $\delta^{18}\text{O}$  of the fluids may be accompanied by variations in wt.% NaCl, such as by mixing of a (deeper) saline fluid and a (shallower) dilute fluid (e.g. Taylor, 1987). Evidence of the mixing of distinct fluids with distinct isotopic ratios and salinities has been reported for some vein deposits of the deep epithermal or 'transitional' category (e.g. Finlandia vein, Peru: Kamilli and Ohmoto, 1977).

Altered sedimentary wall rocks are generally less depleted in  $^{18}\text{O}$  and the hydrothermal fluids are more enriched in  $^{18}\text{O}$  than in volcanic terranes. For example, the markedly higher  $^{18}\text{O}/^{16}\text{O}$  ratios of hydrothermal fluids at Cinola, compared to those at Mt. Skukum and Blackdome (see Fig. 7), can be attributed to higher initial  $^{18}\text{O}/^{16}\text{O}$  ratios of the local waters and to their reaction with sedimentary wall rocks.

Involvement of seawater or low-latitude meteoric water is indicated for the Sulphurets area (Margolis, 1993). Meteoric waters formed the major component of the ore-forming fluids at the Blackdome (Vivian et al., 1987), Dusty Mac (Zhang et al., 1989), and Mt. Skukum (McDonald, 1987) deposits. Data reported in Diakow et al. (1991, 1993) indicate a broadly similar scenario for low-sulphidation deposits of the Toodoggone River area, British Columbia. An unusual range in  $\delta\text{D}$  (-151 to -54 per mil) and  $\delta^{18}\text{O}$  (recalculated: -7.6 to -2.6 per mil) for vein-depositing fluids in the Laforma vein (Table 1; McInnes et al., 1990) are consistent, along with S isotope data, with a mixing scenario involving magmatic volatiles and meteoric waters. Margolis (1993) inferred progressive mixing of magmatic water and seawater during potassic, sericitic, and advanced argillic alteration at Sulphurets, British Columbia, on the basis of isotopic data and water-rock reaction modeling. In some cases (e.g. Creede, Colorado), incorporation of dilute (fresh meteoric) fluids occurred abruptly, and late, in the paragenesis (e.g. Foley et al., 1989).

Recognition of the source of S by means of its isotopic composition depends on the relative mass balance for the contributing sources that are isotopically distinct. Host rock S, or biogenically precipitated S (e.g. Eskay Creek: Roth et al., 1999; Roth and Taylor, 2000, submitted) may comprise a significant component in some low-sulphidation deposits, whereas in high-sulphidation deposits, magmatic S (as  $\text{SO}_2$ ;  $\delta^{34}\text{S}$  about 0-4 per mil for felsic magmas: Taylor, 1987) dominates. Where magmatic sources of wall rock S (e.g. sulphide minerals) dominate, magmatic S isotope values may characterize low-sulphidation deposits also.

Carbon isotope data for calcite or fluid inclusion  $\text{CO}_2$  typically reveals its magmatic (ultimately mantle) origin, even in systems dominated by meteoric water (e.g. Laforma, Yukon: McInnes et al., 1990; Mt. Skukum, Yukon: McDonald, 1987). Admixture with terrestrial C sources may also occur (e.g. organic carbon in the Owen Lake deposit: Thomson et al., 1992).

Fluid inclusions typically have been shown to contain predominantly fluids of low salinity (less than approximately 5 wt.% NaCl<sub>eq</sub>) and have filling temperatures of 150 to 300°C, with maxima in the range of approximately 260 to 280°C (e.g. Equity Silver: Shen and Sinclair, 1982; Blackdome: Vivian et al., 1987). Vapour-dominated systems at or near a boiling water table tend to evolve toward a rather uniform temperature of about 240°C due to the limitation imposed by a maximum in the enthalpy of steam+liquid (e.g. White et al., 1971). Some deep epithermal (transitional) environments close to genetically related intrusions are characterized by higher temperatures, salinities, and  $\text{CO}_2$  contents (e.g. Baker, 2002). The occurrence of fluid inclusions formed at different times in a dynamic system complicates interpretation of the evolution of the system. Temporal changes in the chemical and isotopic compositions of fluid inclusions between different growth zones, or in fracture planes through crystals, demonstrate that the identity of ore-transporting fluids can be obscured by inappropriate sampling and analysis (Foley et al., 1989).

## Geological Properties

### Continental Scale

Exploitation of deposits in active volcanic systems (e.g. Ladolam, Lihir Island, Papua New Guinea: Müller et al., 2002a,b; Carman, 2003), the lure of shallow, easily extracted high-grade deposits, and even the sensational exposure of assay sample adulteration at the Busang epithermal Au prospect, Borneo (e.g. Hutchinson, 1997), have resulted in increased general public awareness of epithermal deposits and mining activities. Recent increase in scientific/technical documentation of deposits, review papers, exploitation of geothermal systems, and laboratory/theoretical studies have helped to clarify geological settings, epithermal Au deposit characteristics worldwide, and clarified processes of transport and precipitation of Au. Large deposits appear to require a sustained (magmatic) heat source, and efficient, localized processes (e.g. cooling, degassing/boiling, fluid mixing, and wall-rock reaction) leading to supersaturation and precipitation of ore minerals. Whether an Au-rich source, especially efficient Au precipitation, or a particular setting or climatic influence is necessary to produce very large deposits remains unanswered (cf. Sillitoe, 1992).

Epithermal Au deposits may be found in association with volcanic activity in numerous tectonic settings, including island-arc volcanoes (e.g. Papua New Guinea: Sillitoe, 1989), and continental-based arcs and volcanic centres (e.g. Silverton caldera, Colorado). The shallow formation of epithermal Au deposits suggests a higher probability of erosion, especially the high-sulphidation deposits that frequently occur in active arc environments. Accordingly, epithermal Au deposits, especially in volcanic terranes, are commonly Tertiary in age, although numerous examples are also known of pre-Tertiary deposits, including the Lower Paleozoic high-sulphidation subtype Gidginbung Au deposit, Lachlan fold belt, New South Wales, Australia (Lindhorst and Cook, 1990). Early Devonian hot spring sinter deposits in Scotland (Nicholson, 1989), and other examples of Paleozoic age are known in Australia, from Queensland (Wood et al., 1990) and the Pilabara Craton (Huston et al., 2002). Even much older, Late Proterozoic epithermal Au deposits are also known: the Hope Brook mine, Newfoundland, (Dubé et al., 1998) and the Mahd adh Dhahab deposit, Arabian Shield (Huckerby et al., 1983). Some deposits of even greater antiquity have survived erosion, deformation, and metamorphism (e.g. Proterozoic Mallery Lake deposit, Nunavut: Turner et al., 2001, 2003), whereas many others were subsequently metamorphosed and deformed (e.g. Paleoproterozoic Enåsen deposit, Sweden: Hallberg, 1994), which inhibits recognition of their epithermal (especially low-sulphidation) origins.

The tectonic setting of epithermal Au deposits is characterized by extension, at least at the district scale or larger, localizing and facilitating emplacement of magma and, at higher levels, hydrothermal fluids. Regional strike-slip fault systems may bind rhomb-shaped extensional zones or pull-apart basins. Fault jogs or transitions from one fault to another create local environments of extension (see also Goldfarb et al., 2004, for similar control on location of intrusion-related Donlin Creek deposit, Alaska). Regionally extensive rift zones can also provide the extensional frame-

work (e.g. Northern Nevada rift: John et al., 2003). The deposits of the Toodoggone River area, British Columbia, for example, are thought to have formed in an elongate, tectonically controlled graben in the medial portion of an island arc (Diakow et al., 1991, 1993). The preservation of these Early Jurassic epithermal deposits may have to do with the fact that the Toodoggone River area was one of active deposition of younger rocks, rather than one of constructional volcanism and uplift, in a climate providing high erosion rates such as found today in Melanesia (e.g. Chivas et al., 1984).

Small volcanic- and volcanoclastic-hosted deposits in Canada are also found in other structural-tectonic settings of a more local nature. These include the Dusty Mac deposit, British Columbia (e.g. Church, 1973; Zhang et al., 1989, Table 15.1-1), located in breccia and stockwork zones along reverse faults at the margin of the White Lake basin. Gold-mineralized zones of silicification and argillic alteration along faults in the Tintina Trench with Eocene rhyolitic dyke, are characterized by superimposed steam-heated or supergene high-sulphidation alteration mineral assemblages (cf. Duke and Godwin, 1986). Sediment-hosted Au ( $\pm$ Ag) deposits occur in a variety of settings in which sedimentary sequences have been intruded by magmas and also in sedimentary rocks not obviously closely associated with intrusions. In some cases, the deposits are located in the outer zones of paleo-hydrothermal systems associated with intrusions (e.g. Cinola; Equity Silver, British Columbia).

### District Scale

Epithermal Au deposits are, in many cases, structurally controlled; the same features that served as the conduits for hydrothermal fluids may have facilitated processes leading to Au deposition (e.g. rapid cooling, boiling, fluid mixing, water-rock reaction, decompression, to name a few). The deposits may be of similar age to their host rocks where these are volcanic, or they may be much younger. A magmatic heat source is commonly inferred. The deposits comprise veins and/or related mineralized breccia and wall rock (e.g. Mt. Skukum), or replacement bodies associated with zones of silicification (e.g. Cinola). Principal geological and other characteristics of each subtype of epithermal Au ( $\pm$ Ag) deposit are listed in Table 2 (see Table 1 for data on individual examples). Both high-sulphidation and low-sulphidation deposit subtypes (distinguished by alteration characteristics) share many features in common. Modern geothermal systems have many features in common with epithermal deposits.

Caldera ring fractures (e.g. Summitville, Colorado: Lipman, 1975), radial fractures (e.g. Lake City, Colorado: Slack, 1980), extensional faulting due to tension above resurgent domes (e.g. Creede, Colorado) may create favourable vein-hosting environments in volcanic terranes. Extensional, pull-apart basins formed between regional strike-slip faults, or at transitions between these faults, provide favourable sites for intrusions and epithermal deposits. Northeast-trending, regional Eocene strike-slip faulting was related to extensional synvolcanic faults at Blackdome, British Columbia, for example, that controlled the emplacement of dykes and Au-bearing quartz veins (Fig. 4). Synchronous tectonic and hydrothermal activity is indicated in some deposits by the fact that many of the vein-bearing

faults were active during and after vein filling (e.g. Blackdome, Mt. Skukum, and Toodoggone River deposits); tectonic vein breccias and displaced mineralized and altered rocks resulted. Similar orientations of normal faults southeast of the Blackdome area and east of the Fraser River-Straight Creek fault have been attributed to northwest extension along the Yalakom fault (e.g. Ewing, 1980; Coleman and Parrish, 1990).

### *Knowledge Gaps*

Tertiary terrane was once thought to be virtually the only fertile ground for the occurrence of epithermal Au deposits. And, certainly, a greater number of important epithermal deposits are known in association with young centres of magmatic activity. Thus, the focus of much of the exploration in Canada for epithermal deposits has been in the Cordillera. Within the last twenty-odd years, however, an increasing number of epithermal Au deposits have been recognized in pre-Tertiary terranes. The apparent metamorphic stability of alunite, recognition of abundant aluminosilicate minerals as potential indicators of pre-metamorphic argillic alteration, and the association of zones of replacement by massive quartz have led to the recognition of high-sulphidation subtype deposits in older terrane, even when the deposits have been extensively deformed (e.g. Hope Brook: Dubé et al., 1998). These discoveries emphasize the need to recognize the preservation of near-surface crust in ancient terranes, and to better understand the tectonic environments and conditions that hold higher potential for such preservation.

Low-sulphidation subtype epithermal Au deposits are harder to recognize in ancient terranes, owing to the facts that their commonly found alteration mineral assemblages are not unique, especially in regional metamorphic terranes, or may no longer be present, depending on the grade of subsequent metamorphism, and that these deposits are often not as intimately associated with igneous rocks as is the tendency for the high-sulphidation subtype deposits. In this case, oxygen isotope techniques can be used to support geological evidence for an epithermal environment by providing a measurable, unique, and robust criterion of near-surface origin of the paleo-geothermal system. Moreover, the distribution of the geothermal system can potentially be mapped using oxygen isotope data, even in deformed rocks. A wider application of this approach could enhance recognition of potentially fertile terrane.

Modern geothermal systems, both subaerial and submarine, commonly associated with centres of active volcanism provide excellent analogs to mineralized epithermal systems (e.g. Cooke and Simmons, 2000). These systems, as well as epithermal districts themselves, should be examined to establish to what extent high-sulphidation and low-sulphidation subtype deposits represent a spectrum of characteristics. The essential contribution of magmatic volatiles to form high-temperature, high-sulphidation alteration, and simply the need of a viable heat source to sustain low-sulphidation systems may explain the apparent lack of a common overlap in space and time.

Where do intermediate sulphidation systems 'fit' in time and space relative to low- and high-sulphidation with respect to the development and evolution of high-level magmatism

and their related geothermal systems? The spatial, geochemical, and chronological links need to be strengthened between deposit subtypes in the classic epithermal Au environment. Notwithstanding the utility of general relationships depicted by schematic cross sections in common usage (e.g. Fig. 15-2 in Poulsen, 1996), a stronger understanding of any such connections between these environments could facilitate the task of the explorationist.

Comparative studies of both poorly and highly mineralized hydrothermal systems need to be undertaken in order to understand and better define characteristics or specific geologic features of a 'regional' nature (e.g. magmatic-hydrothermal evolution with respect to tectonic setting and climate) as possible predictors of better mineralized terrane.

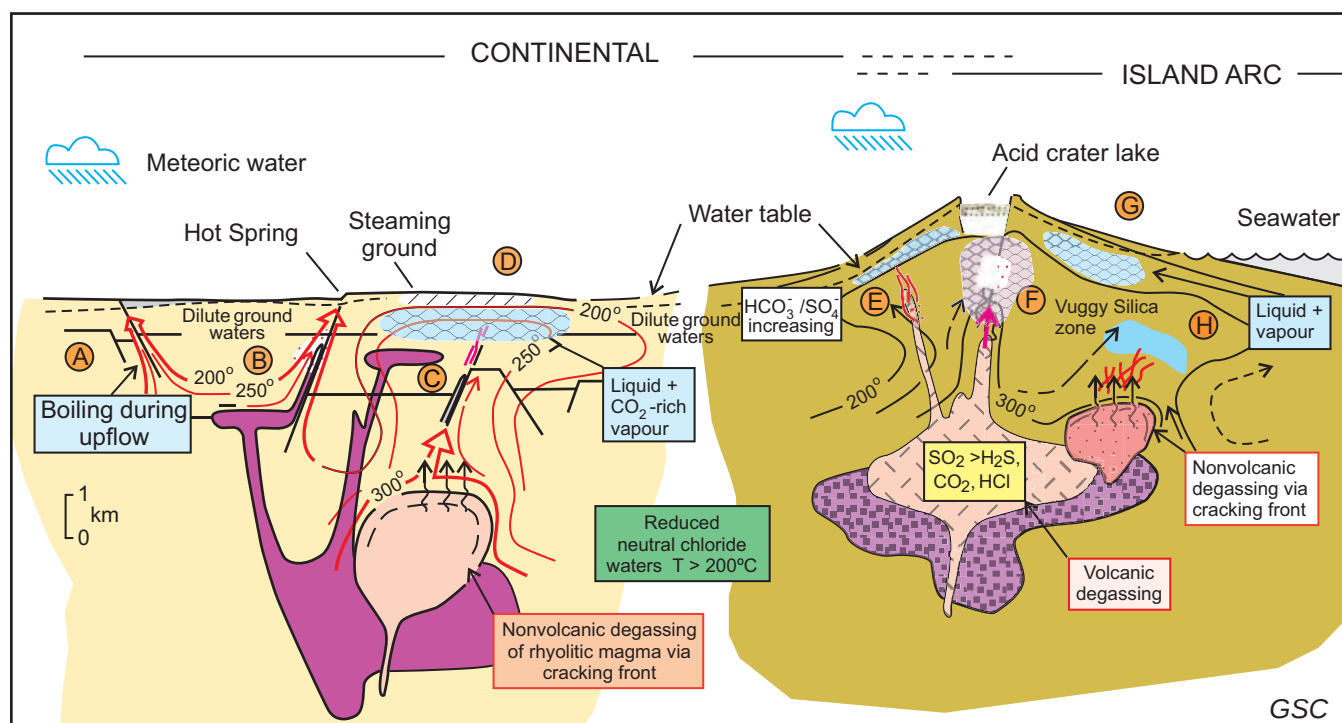
### Deposit Scale

The geological settings of low-, intermediate- and high-sulphidation subtype epithermal deposits are summarized for comparison in Table 2. With respect to a high-level magmatic intrusive centre, the geological properties of these deposit subtypes are broadly those of a 'distal' versus 'proximal' settings, but in both time (relative to magmatic emplacement and active versus passive degassing; e.g., Taylor 1987, 1992). These environments and selected geological properties are illustrated schematically in Figure 8.

The locations of epithermal Au deposits are typically determined by those features that define the hydrothermal system 'plumbing', i.e., provide the hydrological control and control on magmatic emplacement (e.g. structural controls on fluid flow and magmatic emplacement; topographical/paleosurface control of hydrology, boiling elevation, hydrothermal eruption). Extensional faults are especially important, whether due to local, volcanic-related features (e.g. resurgent doming: Creede, Colorado), or to regional tectonism (e.g. rifting zones, or pull-apart basins associated with strike-slip faults: Mt. Skukum, Yukon: Love, 1989; Love et al., 1998; Blackdome, British Columbia: Coleman and Parrish, 1990; R.R. Parrish, pers. comm., 1991; El Peñon, Chile: Arancibia et al., 2006). Fault intersections and fault plane inflections provide zones for vein thickening and zones of brecciation during synchronous movement and vein growth.

High-sulphidation deposits are typically associated with andesitic to rhyolitic rocks and with geologic features associated with sites of active volcanic venting and doming, including among others ring fractures, caldera fill breccias, hot springs, and acidic crater lakes. It is the dominance of directly derived or evolved magmatic fluids that buffer the hydrothermal fluids to low pH and result in the distinct character of the high-sulphidation subtype. Orebodies primarily consist of zones of silica-rich replacement. Bodies of massive 'vuggy silica' and marked advanced argillic alteration mineral assemblages are typical.

Low-sulphidation deposits that occur further removed from active magmatic vents may be more apparently controlled by structural components, zones of fluid mixing, and emplacement of smaller magmatic bodies (e.g. dykes). Meteoric waters dominate the hydrothermal systems, which are more nearly pH neutral in character. Low-sulphidation related geothermal systems are more closely linked to pas-



**FIGURE 8.** Schematic cross-section illustrating the general geological and hydrological settings of quartz-(kaolinite)-alunite and adularia-sericite deposits (from Taylor, 1996; partially adapted from Henley and Ellis, 1983, and Rye et al., 1992). Characteristics shown evolve with time; all features illustrated are not implied to be synchronous. Interpreted settings are indicated for several Canadian deposits discussed in the text; see also Table 1. Local environments and examples of low-sulphidation deposits include: (A) basin margin faults: Dusty Mac; (B) disseminated ore in sedimentary rocks: Cinola; (C) veins in degassing,  $\text{CO}_2$ -rich, low sulphide content, low-sulphidation systems: Blackdome, Mt. Skukum; (E) porphyry-associated vein-stockwork, sulphide-rich (intermediate sulphidation) and sulphide-poor stages: Silbak-Premier; and (H) disseminated replacement associated with porphyry-type and stockwork deposits, involving seawater: Sulphurets. Examples of high-sulphidation environments include: (D and G) steam-heated advanced argillic alteration (quartz-kaolinite-alunite) zone: Toodoggone River district, British Columbia; (F) magmatic-hydrothermal, high-sulphidation vuggy quartz zone ( $\pm$  aluminosilicates, corundum, alunite) Summitville, Colorado, or Nansatsu district, Japan. Fluid flow parallels isotherms. Upflow zones are shown schematically by arrowhead-shaped isotherms. Volcanic degassing refers to magmatic degassing driven by depressurization during emplacement ('first boiling'). Nonvolcanic degassing refers to vapour exsolution during crystallization ('second boiling'). The  $\text{SO}_2$  disproportionates to  $\text{H}_2\text{S}$  and  $\text{H}_2\text{SO}_4$  during ascent beneath environment (F). Note that free circulation occurs only in crust above about  $400^\circ\text{C}$ . All shown temperatures are in Celsius degrees.

sive rather than to active magmatic degassing (if at all), and sustained by the energy provided by cooling, subvolcanic intrusions or deeper subvolcanic magma chambers.

Some deposits with mostly low-sulphidation characteristics with respect to their alteration mineral assemblages have sulphide ore mineral assemblages that represent a sulphidation state between that of high-sulphidation and low-sulphidation deposits. Such deposits tend to be more closely spatially associated with intrusions, and Hedenquist et al. (2000) suggest the term 'intermediate sulphidation' for these deposits.

Zones of boiling, as indicated by mineral textures (bladed carbonate, rhombohedral adularia), are potential sites of Au deposition, especially in low-sulphidation subtype deposits, and that may be related to (and predicted from) paleo-topography. A stationary zone of boiling increases the potential for a high-grade deposit. Similarly, structural control may influence sites of fluid mixing, which can also lead to metal precipitation.

#### Distribution of Canadian Epithermal Districts

Epithermal, deep epithermal/transitional, or intrusion-related deposits in Canada, as illustrated in Figure 1, are primarily found in the Cordillera in close association with centres of magmatism. Although dominantly young (Tertiary) as

a deposit class, older epithermal Au deposits also occur in Canada (Fig. 1, Table 1), or may be suspected in older (even metamorphosed) terranes based on evidence of epithermal alteration. Examples include the low- and high-sulphidation type, Jurassic epithermal deposits of the Toodoggone River area, British Columbia, the low-sulphidation Proterozoic Mallery Lake deposit, Nunavut, and the high-sulphidation Hope Brook deposit, Newfoundland. The Avalonian terrane is notably prospective for both high- and low-sulphidation deposits from the abundant evidence of advanced argillic alteration (e.g. Mills et al., 1999; O'Brien et al., 1999, 2001), and this type of evidence suggests Ordovician terrane in Newfoundland may also be prospective (e.g. O'Driscoll and Wilton, 2005). Whereas advanced argillic alteration can be recognized in metamorphosed terranes, recognition of the origins of sericitic and argillic alteration that formed in high- and low-sulphidation hydrothermal systems may be problematic in metamorphosed terrane on the basis of textural and mineralogical grounds alone. Yet, the existence of ancient unmetamorphosed examples (e.g. Mallery Lake, Nunavut), plus occurrences of deeper, transitional or intrusion-related deposits (Fig. 1), suggest that older deposits remain to be discovered. Exploration of preserved continental volcanic centres and associated epithermal and transitional or intrusion-related deposits in rocks at least as old as the Late Proterozoic should be considered.

### Genetic and Exploration Models

Stable isotope and fluid inclusion studies have contributed significantly to our knowledge of the origins, pressures, temperatures, and chemical compositions of hydrothermal fluids responsible for epithermal Au deposits. Studies of modern geothermal systems, hot springs, and volcanic gases have greatly increased our understanding of epithermal deposits because active geothermal systems offer modern-day analogs for physical and chemical parameters that can be directly measured, and compared to inferences made from ancient water-rock interaction and alteration zones (Hedenquist et al., 2000). For example, comparisons between active, steam-dominated geothermal systems like the Geysers-Clear Lake system, California, and hot-spring deposits such as Cinola, British Columbia or the McLaughlin deposit, California (Sherlock, 2005) aid the interpretation of features of hot-spring deposits in the geologic record, and add quantitative constraints on parameters of formation, metal segregation, and concentration.

Determination of mineral solubility, metal volatility and transport, and phase relations, as well as numerical water-rock reaction simulations, have contributed to our quantization of the chemical and physical nature of mineralizing hydrothermal fluids, and also to our understanding of the processes that lead to the transport and deposition of Au, Ag, and base metals.

Lindgren (1922, 1933) suggested that degassing magmas are sources of many ore-forming constituents in epithermal Au deposits, and this supposition appears to be essentially correct for magmatic-hydrothermal high-sulphidation deposits (Stoffregen, 1987; Rye et al., 1992). However, for many deposits (e.g. the majority of low-sulphidation subtypes) O- and H-isotope data permit only a very small fraction (i.e. <10%) of the hydrothermal water to be of magmatic origin, despite the close association of some deposits with cooling magmatic rocks, whereas C and S isotope studies indicate a significant magmatic contribution in many cases. Thus, a mineralizing fluid can have a complex origin, one involving links to degassing magmas as well as the dominance of local recharge waters to fuel the hydrothermal system.

Schematic cross-sections illustrating the principal physical environments of low-sulphidation and high-sulphidation epithermal vein and hot-spring deposits and their related geothermal systems are shown in Figure 8. This figure emphasizes features of genetic significance found in at least some of the more prominent Canadian deposits.

Slow-cooling epizonal plutons, such as those shown in Figure 8, may undergo 'subvolcanic' (passive) degassing as they crystallize (i.e. (second boiling)) rather than 'volcanic' (active) degassing, and can provide mineralizing constituents to overlying or adjacent meteoric hydrothermal systems via protracted leakage of magmatic volatiles across cracking fronts at the margins of the crystallizing magma. Variations on this theme derive also from differences in the S content of rhyolitic (lower) to andesitic (higher) magmatic volatiles, from differences in crustal level at which magmatic degassing occurs, and from the relative proportions of magmatic and meteoric fluids involved through time. Additional discussion can be found, for example, in Henley (1985), Stoffregen (1987), White and Hedenquist (1990),

Giggenbach (1992), Rye et al. (1992), Sillitoe (1993), and Heinrich et al. (2005).

The two principal (end-member) geochemical environments of epithermal mineralization and alteration are determined largely by the dominance in each case of two different fluids. On the one hand, magmatic-hydrothermal environments that are dominated (buffered) by acidic, magmatic fluids containing CO<sub>2</sub>-, HCl-, and SO<sub>2</sub>-rich vapour produce high-sulphidation mineral assemblages characterized by oxidized forms of iron (e.g. hematite) and S (e.g. alunite), and by base leaching of wall rocks leaving marked (residual) silica enrichment. This environment may overlie porphyry systems (Sillitoe and Bonham, 1984). On the other hand, near neutral, more reduced, meteoric-dominated waters containing Cl, H<sub>2</sub>S, and CO<sub>2</sub>, yield low-sulphidation (adularia-sericite) mineral assemblages through hydrolysis reactions involving feldspar in the wall rocks. The chemical state of these fluids becomes largely wall-rock buffered.

Two fundamentally different hypotheses regarding the source of Au in epithermal deposits are (1) metals are supplied directly by actively or passively degassing magma (e.g. Taylor, 1987; 1988) that also provides heat to the paleo-hydrothermal system, and (2) the metals are leached from the rocks that host the geothermal system. On the one hand, isotopic confirmation of the importance of meteoric waters has encouraged proponents of the second hypothesis. On the other hand, isotopic data also indicate that S and C are of magmatic origin in certain deposits (e.g. Summitville, Colorado: Rye et al., 1992) and in active geothermal systems (e.g. Taylor, 1987). Symonds et al. (1987) demonstrated the transport and variable degrees of volatility of precious and base metals, and their association with magmatic Cl, C, and S, by sampling and analyzing very high-temperature volcanic gases. Metals and other constituents were shown to separate upon cooling, illustrating the potential for direct magmatic contribution to geothermal systems and for temperature-related metal zoning.

At magmatic temperatures, Au solubility is high in Cu-Fe sulphides, which may represent a significant Au source depending on the passive degassing history of a porphyry-forming magma (e.g. Kesler et al., 2002). The oxidation state or sulphide activity of magma at initial vapour saturation, for example, might influence the amount of extractable Au that could be contributed to associated epithermal deposits. From the phase relations of NaCl brines and calculated fluid speciation from 150 to 450°C involving brine, S, and Au, Heinrich et al. (2004) proposed that an excess of sulphide over Fe in an exsolved, one-phase Au-rich magmatic fluid is essential for the transport of Au to the hydrothermal system (see also Heinrich, 2005). The presence of Au in vapour-dominated portions of hydrothermal systems, the sublimation of metals from volcanic vapours (e.g. Symonds et al., 1987), the separation of base and precious metals in epithermal deposits (Buchanan, 1981), and phase-relations and experimental data (Williams-Jones and Heinrich, 2005), suggest that significant amounts of Au can be transported by a low-density (subcritical) fluid upon phase separation from the initially exsolved magmatic fluid.

Alteration mineral assemblages are characteristic of two end-member chemical environments of alteration and miner-



erous and dilute fluids and consequent metal precipitation (via cooling, dilution, and oxidation) are clearly demonstrated.

Simple, conductive cooling of Au-bearing fluids is sufficient to cause Au precipitation (see Fig. 9). Boiling can also cause cooling, chemical fractionation, and an increase in pH associated with acid vapour loss that leads to saturation and precipitation of chloride-complexed metals (e.g. Cu, Pb, Zn: Drummond and Ohmoto, 1985; Spycher and Reed, 1989; Williams-Jones and Heinrich, 2005). Also, degassing of initially CO<sub>2</sub>-rich fluids in gas-rich systems depletes the liquid in H<sub>2</sub>S that is carried off in a CO<sub>2</sub>-rich vapour. The loss of H<sub>2</sub>S eventually leads to precipitation of sulphide-complexed metals (e.g. Au; Drummond and Ohmoto, 1985; Henley, 1985; Hayashi and Ohmoto, 1991). Carbon dioxide and hydrogen sulphide are well correlated in some geothermal fluids (Fig. 11 in Taylor, 1987). Boiling and chemical fractionation of the hydrothermal fluid provides an explanation for the separation of precious and base metals. This separation results in a vertical zoning where fluids are upwardly flowing (Clark and Williams-Jones, 1990), or in relative temporal stages, such as at Silbak-Premier, British Columbia, and El Indio, Chile. As a corollary, larger vein deposits require the movement of larger amounts of fluid through localized zones of boiling, and thus the importance of structural analysis in exploration is obvious. Neutralization and cooling of ore fluids may also occur (1) by mixing with dilute groundwaters, and (2) by water-rock reaction (e.g. sulphidation of ferrous iron-bearing minerals), especially during formation of disseminated and replacement-type orebodies.

Steam-heated acid waters formed by the oxidation and condensation of H<sub>2</sub>S (boiled off deeper geothermal reservoirs) in groundwater produce high-sulphidation subtype alteration of the volcanic rocks (Henley and Hedenquist, 1986). The Champagne Pool, in the CO<sub>2</sub>-rich Waiotapu geothermal field (steam-heated, high-sulphidation subtype alteration), New Zealand, is a hydrothermal eruption feature below which Au and Ag are being deposited in response to boiling and loss of H<sub>2</sub>S over the approximate temperature interval 250 to 175°C (Hedenquist, 1986). Ore-grade, Au-bearing amorphous sulphides precipitate in the pool at 75°C, and base metal sulphides occur below the zone of boiling. Acidic waters produce advanced argillic alteration and, with variation in P<sub>CO2</sub>, evolve to cause the replacement of adularia and albite by sericite. Thus, by chemical evolution, a geothermal field, initially boiling and producing high-sulphidation subtype alteration, may eventually produce minerals characteristic of low-sulphidation subtype alteration.

The precious metal content of steam-heated alteration zones may also be related to the rate of fluid ascent versus the extent of boiling and H<sub>2</sub>S loss: faster moving fluids and/or those less depleted in H<sub>2</sub>S may produce higher grades of precious metals in steam-heated alteration zones. This might apply to the ascension of boiling magmatic hydrothermal plumes as well as to boiling meteoric and marine geothermal fluids.

Exploration for epithermal Au deposits entails, for a comprehensive approach, judicious application of methodologies to assess the geological characteristics (e.g. tectonic/struc-

tural setting, petrological association, mode of occurrence, geochronology), mineralogical and geochemical characteristics (mineral assemblage, mineral/rock chemical compositions, isotopic composition, exploration geochemical techniques), and geophysical characteristics (e.g. electrical and magnetic properties). The results of the application of these techniques are compared to one or more 'models' that represent empirically determined associations of characteristics. Hedenquist et al. (2000) is a useful and comprehensive reference in this regard.

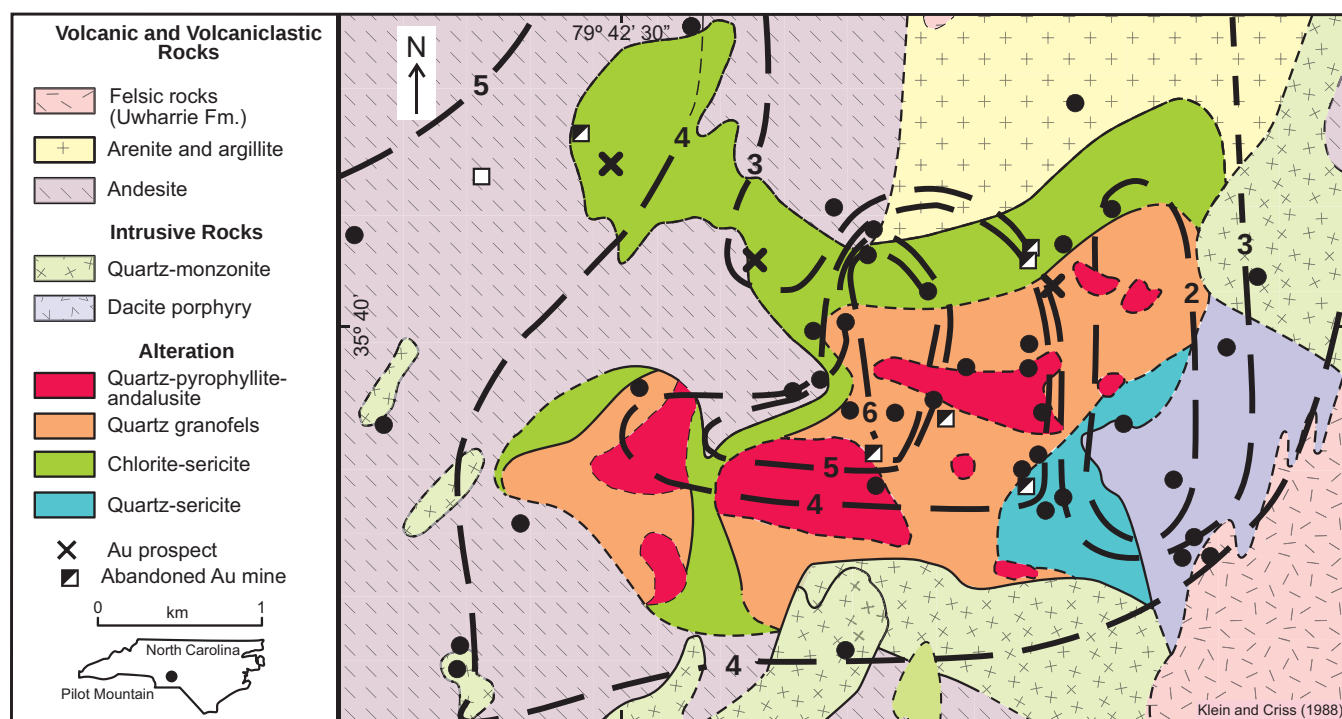
#### *Assessment of Geological Characteristics*

Volcanic arcs and belts with abundant intermediate to felsic rocks and associated rift systems host epithermal Au deposits of many ages. Evidence of high-level magmatism in more deeply eroded terrane may still offer possibilities for transitional or intrusions-related deposits. Geologic mapping, including alteration of mineral assemblages, and attention to structural control(s) provides a fundamental means of assessment.

#### *Assessment of Mineralogical and Geochemical Characteristics*

Mapping and recognition of alteration mineral assemblages are reasonably straightforward in unmetamorphosed terrane. New instrumental technologies, such as Short-Wave Infrared Spectroscopy (SWIR; e.g., PIMA®, Portable Infrared Mineral Analyzer; Ducart et al., 2006), in addition to portable (to field offices) XRF analyzers and X-Ray diffractometers, are finding increased application for mineralogical and elemental identification in the field. In deformed and metamorphosed terranes, however, interpretive mineralogical or alteration mapping may be problematic. In particular, distinction of high-sulphidation alteration formed in steam-heated zones (which may form above either high- or low-sulphidation systems), from high-temperature alteration may affect interpretation of the deposit subtype and exploration strategy. The nature and origin of highly silicic zones should also be determined, particularly in deformed terranes where the usual textural criteria may no longer be applied. Oxygen isotope mapping, using whole-rock analysis, can be used to map paleo-hydrothermal systems, even in highly metamorphosed and deformed terranes. In particular, oxygen isotope techniques can be especially useful to decipher the origins of chlorite-sericite-bearing mineral assemblages, and assist in interpreting the origins (e.g. residual, vuggy silica zone from silicic zones from near-surface, lower temperature silicification).

Two applications of oxygen isotope techniques for the exploration of epithermal Au deposits are shown in Figures 10 and 11 representing examples of high-sulphidation and low-sulphidation systems, respectively. The Pilot Mountain area in the Carolina Slate Belt contains a number of previously mined high-sulphidation epithermal Au deposits. The greenschist-metamorphosed terrane bears mineralogical evidence of argillic and advanced argillic alteration shown on the basis of oxygen isotope characteristics (Klein and Criss, 1988) to have formed in a meteoric-water recharged, high-sulphidation system. Isotopic zoning above the associated high-level stock documents upflow of magmatic-hydrothermal fluid that was most intense in the area of vuggy silica



**FIGURE 10.** A  $\delta^{18}\text{O}_{\text{WHOLE-ROCK}}$  isopleth map of the high-sulphidation epithermal Au district of Pilot Mountain in the Carolina-Avalon slate belt, Randolph County, North Carolina (after Klein and Criss, 1988). Klein and Criss (1988) infer the greenschist metamorphosed terrane to be westward tilted, exposing a vertical section through part of a high-level quartz monzonite stock, dacite porphyry, and argillic and advanced argillic alteration zones at the apex of the stock. Areas mapped as 'quartz granofels' are interpreted to represent a metamorphosed 'vuggy silica' zone associated with Au (note greater number of Au mines). Alteration and mineralization at Pilot Mountain are analogous to that at the Hope Brook mine, Newfoundland (Dubé et al., 1998), and similar to areas of high-sulphidation alteration of broadly similar age in the Burin and Avalon Peninsulas, Newfoundland (see discussion in text). Fifty-three samples, virtually all of which yielded low  $\delta^{18}\text{O}_{\text{WHOLE-ROCK}}$  values, record a near-surface, meteoric water-recharged geothermal system over an area of more than 30 km<sup>2</sup> (larger than the 4 x 6 km area shown). The relative increase in  $\delta^{18}\text{O}_{\text{WHOLE-ROCK}}$  in altered rocks above the stock probably reflects the upflow of isotopically heavier, magmatic-hydrothermal fluids. Mapped anomalies of Au, Mo, Sn, Cu, and B in soil samples agree well with isotopically mapped zones of magmatic-hydrothermal influence (Klein and Criss, 1988). Continued hydrothermal upflow is indicated by the northwest-trending zone of chlorite-sericite; a higher density of samples would permit a more detailed isotopic definition of hydrothermal flow patterns.

alteration and Au mineralization (Fig. 10). The isotopically mappable effects of related meteoric hydrothermal alteration cover at least 30 km<sup>2</sup>, well beyond definitive mineralogical zones, and distinguish this area from other, non-mineralized sites of plutonism in the slate belt (Klein and Criss, 1988). The application of this technique to mapping meteoric high-sulphidation systems in undeformed terrane is straightforward (e.g. Tonopah, Nevada: Taylor, 1973), whereas the study at Pilot Mountain demonstrates the potential of this technique for exploration in older terranes.

Oxygen isotope zoning about veins in the low-sulphidation epithermal Au deposit at Hishikari, Japan (Fig. 11) shows definitive effects of hydrothermal water/rock interaction in a surface zone as much as 200 m or more in length above blind vein deposits. Whereas clay mineral alteration can also be recognized and mapped at the surface of this young unmetamorphosed deposit (Izawa et al., 1990), whole-rock oxygen isotope anomalies as telltale indicators of epithermal fluid flow can survive even high-grade regional metamorphism.

Soil and rock geochemical analyses may prove fruitful. The Pilot Mountain, North Carolina, district (Keith and Criss, 1988; see also caption to Fig. 10) provides a particularly good example, in a greenschist-facies metamorphic terrane, of the correspondence between mineralogical alteration, oxygen isotope zoning, and geochemical soil anom-

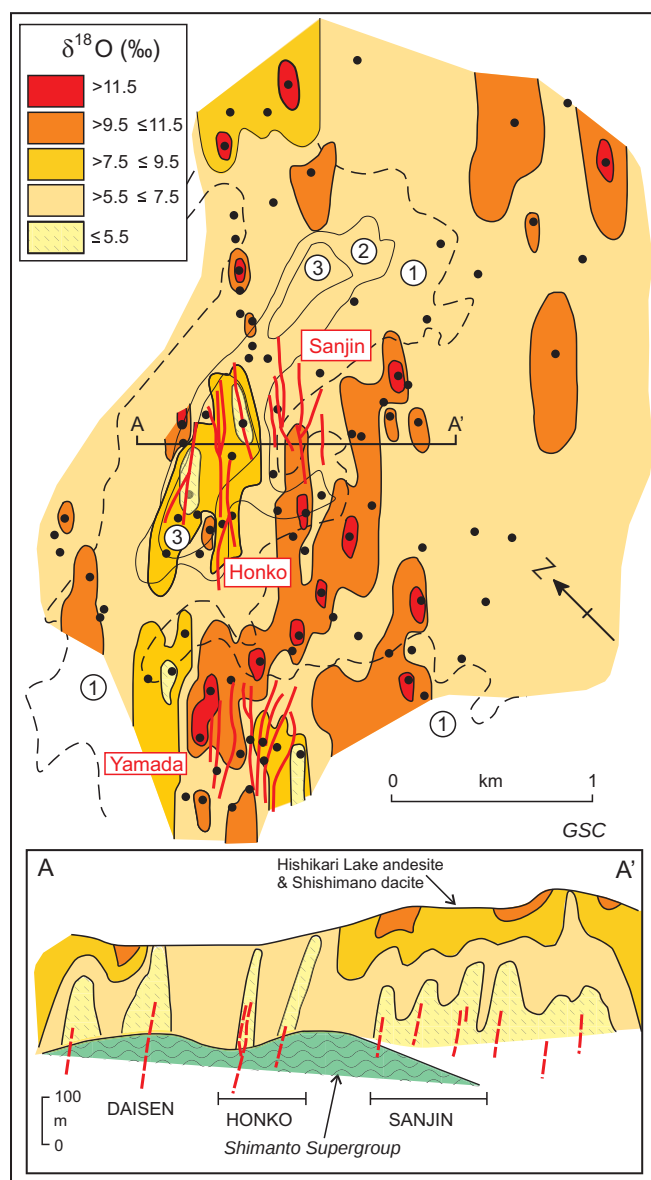
alies. In Canada, geochemical mapping of the typical epithermal pathfinder elements (Hg, Sb, As, Tl, in addition to Au and Ag), plus 'intrusion-related' elements (e.g. Mo, Cu, Sn, B) may also be tested in both soil and till, as well as rocks. Aluminosilicates, corundum, sulphides, specular hematite, and alunite may, among other minerals, also prove useful in till analysis.

#### *Assessment of Geophysical Parameters*

In contrast to their application in the exploration of other types of ore deposits, geophysical techniques have been less useful in the discovery of epithermal deposits (Sillitoe, 1995; Hedenquist et al., 2000). Except for the use of aeromagnetic surveys as a very powerful aid in regional geologic mapping, the application of other geophysical techniques for epithermal Au deposits in Canada appears less fruitful.

#### *Knowledge Gaps*

Upon comparison of many features, both regional and local, of 16 bonanza (>30 tonnes Au) and giant (>200 tonnes Au) epithermal Au deposits, Sillitoe (1992) concluded that, although complex arc environments and unusual igneous rock types seemed more prospective, no single feature could be isolated as an apparent cause or explanation. Either an unusually rich source of Au or an unusually effective depositional process was necessary to effect such concentrations



**Figure 11.** The  $\delta^{18}\text{O}$  isopleth map and cross-section of the low-sulphidation vein Au deposit at Hishikari area, Japan, from Taylor (1996; based on data in Naito et al., 1993) show oxygen isotope zoning of altered wall rocks associated with vein emplacement and mineralization (see also Faure et al., 2002). Positions of Daisen quartz vein, Honko vein system, and Sanjin vein system (shown in red) are projected to surface and into the plane of section A-A'. Oxygen isotope data of Naito et al. (1993) were recontoured to emphasize the structural control of fluid flow indicated by oxygen isotope zoning. Fresh andesite and dacite are presumed to have a whole-rock  $\delta^{18}\text{O}$  value of 8.5‰ (Naito et al., 1993). Locations of whole-rock oxygen isotope samples are shown by filled circles, but the locations of subsurface samples, which provide the basis for the isotopic zoning pattern in the cross-section, are omitted for simplicity. Alteration mineral zones (after Izawa et al., 1990) are (1) chlorite-smectite and/or sericite-smectite; (2) quartz-smectite and/or kaolin minerals; and (3) cristobalite-smectite+kaolinite or halloysite. Chlorite-sericite alteration dominates at depth. Note that prospective is optically extended to the surface, some 200 m in many cases, above blind vein deposits.

of Au. This ‘chicken or egg’ conclusion remains as a principal enigma, a key question in the knowledge gap. A complete spectrum in Au endowments in epithermal deposits worldwide might be expected if Au endowment depended only on the Au content of the source materials. Sillitoe (1992)

emphasized the necessity for the “geologically unexpected” in the environments of these rich deposits and the likelihood that this factor resulted in usually effective Au precipitation. Despite many detailed studies since Sillitoe’s paper (1992), universal agreement on this central question appears to elude.

A firmer understanding of links between porphyries and epithermal systems is evolving, and an understanding of the temporal differences in magmatic and hydrothermal evolution that explains the lack of direct linkages (e.g. low-sulphidation and porphyry Cu-Au deposits). Efficient trapping of hydrothermally transported Au is certainly required for an economic deposit, and processes such as mixing, boiling, cooling, and oxidation are known to have occurred at the time of gold precipitation (e.g. Hayashi et al., 2001). As a corollary, further studies of the processes of magmatic degassing (both active and passive), associated metal migration, and the influence of the oxidation state of the magma on metal availability and migration would seem to be helpful.

A sufficient number of ancient epithermal Au deposits, both low- and high-sulphidation subtypes, are now known to raise the level of understanding needed regarding the likelihood of preservation and rates of destruction of the epithermal regime of the crust. Clearly very old examples have survived.

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