Reduced Intrusion-related Gold Systems

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Abstract

Reduced intrusion-related gold systems (RIRGS) are characterized by widespread arrays of sheeted auriferous quartz veins that preferentially form in the brittle carapace at the top of small plutons, where they form bulk-tonnage, low-grade Au deposits characterized by a Au-Bi-Te-W metal assemblage, such as the Fort Knox and Dublin Gulch deposits. RIRGS also include a wide range of intrusion-related mineral deposit styles (skarns, replacements, veins) that form within the region of hydrothermal influence surrounding the causative pluton, and are characterized by proximal Au-W-As and distal Ag-Pb-Zn metal associations, thereby generating a zoned mineral system. Plutons that generate RIRGS form in tectonic settings characterized by weak post-collisional extension behind a thickened continental margin. Such settings are also conducive to the formation of W deposits, and thereby generate a regional Au-W metallogenic association, but individual plutons can generate both W and Au deposits. Associated magmas are diverse and have characteristics of I-, S-, and A-type granitoids. The most prolific Au systems comprise metaluminous, moderately reduced, moderately fractionated, biotite>>hornblende>pyroxene quartz monzonites that have mixed with volatile-rich lamprophyric melts. The magmas have a reduced primary oxidation state that form ilmenite-series plutons. This reduced state causes associated sulphide assemblages to be characterized by pyrrhotite, and quartz veins that host methane-rich inclusions. RIRGS mostly form at a depth of 5 to 7 km and generate mineralizing fluids that are low salinity, aqueous carbonic in composition and are, therefore, unlike typical porphyry Cu deposits. The RIRGS class was developed on well-studied examples in Yukon and Alaska. Other suggested Canadian examples are in southeastern British Columbia and New Brunswick; numerous global examples have been suggested, but many are controversial.

Résumé

Les systèmes aurifères associés à des intrusions réduites (SAAIR) sont caractérisés par des réseaux étendus de filons de quartz aurifère dans des zones feuilletées, qui se forment de manière préférentielle dans la carapace à déformation fragile développée au sommet de petits plutons. Ces systèmes filoniens aurifères forment des gîtes d'or à faible teneur caractérisés par une association métallique à Au-Bi-Te-W comme les gisements de Fort Knox et de Dublin Gulch. Les SAAIR englobent également une gamme étendue de styles de minéralisations associés à des intrusions (skarns, gîtes de remplacement, gîtes filoniens) qui se forment dans la zone d'influence hydrothermale entourant le pluton auquel ils doivent leur formation et qui sont caractérisés par des associations métalliques de nature proximale à Au-W-As et de nature distale à Ag-Pb-Zn , produisant ainsi des systèmes à zonalité minérale. Les plutons engendrant des SAAIR se forment dans des cadres tectoniques caractérisés par une faible extension consécutive à une collision à l'arrière d'une marge continentale épaissie. De tels cadres sont également favorables à la formation de gîtes de tungstène, engendrant ainsi une association métallogénique régionale à Au-W, mais des plutons individuels peuvent produire des gîtes de W et des gîtes de Au. Les magmas associés sont divers et présentent des caractéristiques des granitoïdes des types I, S, et A. Les systèmes aurifères les plus prolifiques renferment des monzonites quartziques à biotite>>hornblende>pyroxène modérément réduites, modérément fractionnées et de caractère métalumineux, qui se sont mélangées à des bains lamprophyriques riches en matières volatiles. Les magmas présentent un état d'oxydation initial réduit qui produit des plutons de la série de l'ilménite. Cet état réduit fait en sorte que les paragenèses sulfurées associées sont caractérisées par la pyrrhotine et que des filons de quartz renferment des inclusions riches en méthane. Les SAAIR se forment principalement à des profondeurs de 5 à 7 km et engendrent des fluides minéralisateurs aquo-carboniques de faible salinité, qui sont ainsi différents de ceux qui caractérisent les gîtes porphyriques de cuivre. La classe des SAAIR a été élaborée d'après des exemples bien étudiés au Yukon et en Alaska; d'autres exemples sont proposés au Canada dans le sud-est de la Colombie-Britannique et au Nouveau-Brunswick alors que de nombreux exemples ont été proposés ailleurs dans le monde, mais plusieurs d'entre eux restent controversés.

Definition

Reduced intrusion-related Au systems (RIRGS) include a wide range of Au-only mineral deposit styles that are considered to have had a direct genetic link with a cooling felsic intrusion during their formation. Associated deposit styles may be as varied as skarns, veins, disseminations, stockworks, replacements, and breccias (Hart et al., 2000a) and, therefore, define ores that are broader in classification than simply a deposit and were thus identified as a system (Lang et al., 2000). The most diagnostic deposit style within the RIRGS classification is intrusion-hosted, sheeted arrays of thin, low-sulphide quartz veins with a Au-Bi-Te-W signature, which typically comprise bulk tonnage, low-grade Au resources. The host or associated intrusions characteristically have moderately low primary oxidation states, making them reduced, ilmenite-series (Ishihara, 1981) granitoids. The best

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examples of RIRGS include Fort Knox (Alaska) and Dublin Gulch (Yukon).

These gold systems have only been recognized as a new deposit class since 1999 and, as such, are in a juvenile state of understanding with still rapidly evolving data collection, interpretation, and nomenclature (see Hart, 2005 for details; see Mair et al., 2006a as a current example). As an example of nomenclature evolution, many of these dominantly intrusion-hosted systems were originally considered to be Au porphyry deposits (Hollister, 1992; Sinclair, 2007), whereas country rock-hosted disseminated and stockwork systems dominantly distal to plutons were considered to be “Carlin-like” deposits (Poulsen 1996). RIRGS are distinct from intrusion-related Au deposits as defined by Sillitoe (1991, 1995), because the deposits are characteristically associated with porphyry Cu systems that are related to highly oxidized and more mafic intrusions. Therefore, within the intrusion-related clan, two different types of Au mineralizing systems can be identified using the prefixes “reduced” and “oxidized”. The RIRGS are a distinct class that lacks anomalous Cu, have associated W, low sulphide volumes, and a reduced sulphide mineral assemblage, and that are associated with felsic, moderately reduced (ilmenite-series) plutons, whereas oxidized intrusion-related Au deposits are mostly Au-rich (or relatively Cu-poor) variants of the porphyry Cu deposit model associated with more mafic, oxidized, magnetite-series plutons.

Intrusion-hosted, sheeted-vein styles of mineralization typically occur in all associated RIRGS plutons to some degree, but the classification can include skarns, replacements, disseminations, veins, and stockworks that may develop within, beyond, or above the pluton’s thermal aureole. However, except for the skarn deposit model which has long recognized a “reduced” variant (Einaudi et al., 1981; Meinert, 1998), specific deposit models for the other Au mineralization styles are lacking because such styles are common to many deposit types. Shallow-level equivalents of RIRGS such as Brewery Creek occur locally and are termed “epizonal”. Intrusion-related Au-bearing vein deposits certainly occur, but their characteristics are so varied that establishing a set of defining characteristics to construct a model has proven difficult (e.g., Sillitoe and Thompson 1998). This has, in part, resulted in considerable confusion in distinguishing intrusion-related Au and orogenic Au vein deposits (variably discussed in Goldfarb et al., 2000, 2005; Hart et al., 2002; Groves et al., 2003; Hart and Goldfarb, 2005). Herein, the characteristics of RIRGS are defined and distinguished from other deposit types.

Distribution

Canada

The RIRGS classification was developed in response to exploration and Au deposit discoveries in the 1990s in Alaska (USA) and Yukon (Canada) in the northern North American Cordillera (Fig.1). The most significant economic mineralization is in the Fairbanks area of central Alaska, where the actively mined Fort Knox deposit (Bakke, 1995) serves as a type example of a RIRGS. Significant but unmined systems occur at Dublin Gulch (Hitchins and Orssich, 1995; Maloof et al., 2001), Scheelite Dome (Mair et al., 2000, 2006a) and Clear Creek (Marsh et al., 2003), where they form the core of the Tombstone Gold Belt in the central Yukon. All of these Tombstone Gold Belt systems are hosted mainly in, and directly formed from, reduced mid-Cretaceous (95–91 Ma) plutons that define a discontinuous belt that spans 1000 km across central Yukon and Alaska (Hart et al., 2004a).

This RIRGS model was adopted in the late 1990s to classify many Au deposits and districts throughout interior Alaska and Yukon, and assembled into the vast Tintina Gold Province (TGP; Tucker and Smith, 2000). However, many of the identified deposits and districts in the TGP lack Au ores with RIRGS characteristics or are dominated by placer Au deposits with uncertain lode sources (Hart et al., 2002). Although the TGP contains many important RIRGS, it also includes other types of lode Au deposits. Thus, the >800 km-long Tombstone Gold Belt best describes the distribution of the unequivocal RIRGS, whereas TGP describes a large geographical area with a significant Au endowment (Fig. 1).

Elsewhere in the Cordillera, “plutonic-related” systems with some similar characteristics to RIRGS are associated with Cretaceous Bayonne suite intrusions in southeastern British Columbia (Fig. 2), where they form a 350 km-long belt (Logan et al., 2000). Outside of the Cordillera, the best known Canadian examples may be those in the Acadian orogeny of southern New Brunswick (McLeod and McCutcheon, 2000), such as Clarence Stream and Lake George, although these are better known for their W-Sn-Mo-Sb mineralization. Potential Archean examples in Canada have been suggested to occur in the southern Superior Province of Ontario and Quebec (Robert, 2001; Malartic, Fig. 2), but these deposits may be distinct because they are unlike typical RIRGS.

Global

Although the RIRGS classification is still developing, numerous Phanerozoic global examples suggested in early compilations, such as those of Thompson et al. (1999), Thompson and Newberry (2000), and Lang et al. (2000), have defined a preliminary distribution that indicates potential RIRGS in Paleozoic and Mesozoic orogenic belts, although supporting documentation for these classifications is mostly lacking. Suggested examples include the Bolivian Polymetallic Belt, Yanshanian orogen of the North China craton, Tien Shan of central Asia, New England and Lachlan provinces in Australia, and the Bohemian Massif and the Iberian Peninsula in Europe (Fig. 2). Specific deposits include Timbarra (Mustard, 2001), Kidston (Baker and Tullemans, 1990), and potentially other Au deposits in eastern Australia (Blevin, 2004); Penedona and Jales (Portugal), Salave and Solomon (Spain), Mokrsko and Petrackova hora (Czech Republic), Vasilkovskoe (Kazakstan), Niuxinshan (China), Sn-rich Kori Kollo (Bolivia), and Petza River and Miller Mountain (USA; Thompson et al., 1999; Lang and Baker, 2001). Some Paleozoic Au giants in central Asia have been interpreted by some workers (e.g., Cole et al., 2000; Wall et al., 2004) to show features that resemble RIRGS (i.e., Jilau, Muruntau, Sukhoi Log, Kumtor), but such associations are highly controversial and many workers argue that these

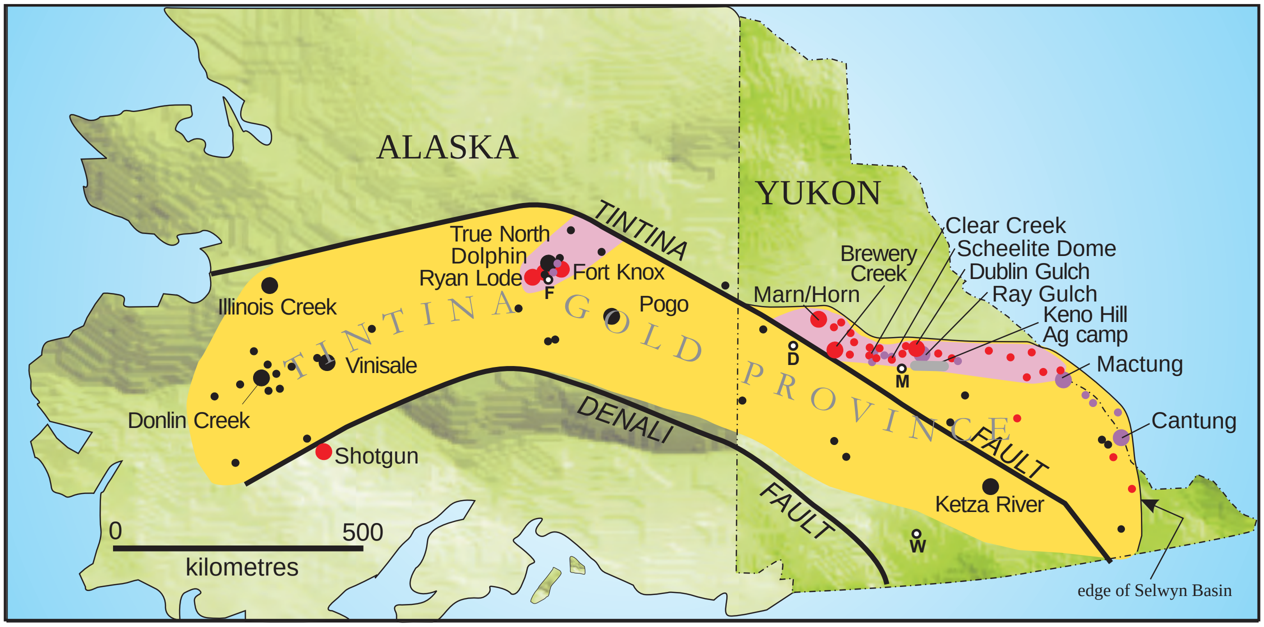

Figure 1. Distribution of the Tintina Gold Province (TGP) across Alaska and Yukon as shown in yellow. Individual Au deposits (large circles), notable occurrences, and those mentioned in the text (small circles) are shown. Not all Au mineralization in the TGP represents RIRGS. Gold deposits and occurrences considered to be RIRGS are shown in red; those that are ambiguous or controversial in origin are highlighted in black; and those dominated by W, but associated with the same plutonic event as RIRGS, are shown in purple. The RIRGS that define the Tombstone Gold Belt (shown in pink) underlie central Yukon; its western extent has been offset along the Tintina Fault and displaced to its present location, where it forms part of the Fairbanks district. Notably, the TGP is composed of numerous different Au districts with varying deposit types and ages of mineralization, but reduced intrusion-related Au systems are mostly limited to the Tombstone Gold Belt. F=Fairbanks, D=Dawson, M=Mayo, W=Whitehorse.

deposits are likely orogenic Au deposits (Groves et al., 2003; Goldfarb et al., 2005).

Global Archean and Proterozoic RIRGS examples have also been suggested, but Proterozoic examples such as Tennant Creek and Telfer (Rowins, 2000) in northern Australia are Cu-rich and lack most RIRGS characteristics. Similarly, Boddington (McCuaig et al., 2001) and Tower Hill (Witt, 2001), both of Western Australia, have been suggested as Archean examples, but mostly lack critical RIRGS features, and indicate the unlikelihood of formation or preservation of good Archean examples.

Time

The mid-Cretaceous was the most favourable time for formation of RIRGS along Canada's western margin, in adjacent eastern Alaska, and in southeastern British Columbia. Some southwestern Alaskan suggested examples, such as Shotgun, are latest Cretaceous. The less well understood occurrences in New Brunswick are Devonian. Globally, although there is still much controversy as to what deposits truly are RIRGS, the Phanerozoic appears to clearly dominate, particularly the Cretaceous and the mid-Paleozoic (Devonian to Carboniferous), which were the most favorable times for formation of RIRGS. Proterozoic and Archean examples are controversial and too few to assess in terms of timing, but the lack of W deposits of these ages emphasizes the unlikelihood of this as a significant era.

Grade and Tonnage

The grades and tonnages of deposits classified as RIRGS are wide-ranging due to the variation of deposit styles within the classification. The variation further broadens with the inclusion of controversial Alaskan deposits, such as the high-grade Pogo and large tonnage Donlin Creek orebodies. Figure 3 shows the grade-tonnage relationships for most of the suggested Canadian and Alaskan examples, as well as Timbarra in Australia.

The most characteristic deposit style, intrusion-hosted sheeted vein deposits, is best represented by mineralization at Fort Knox and Dublin Gulch. Both deposits have minable reserve grades of approximately 0.9 g/t Au and cutoffs of 0.4 to 0.5 g/t, but at Fort Knox, material as low as 300 ppb Au may be stockpiled. The grades of individual veins are 5 to 50 g/t Au, but most ore blocks have an average of 3 to 5 veins per metre within otherwise barren host rocks, thus yielding ~1 g/t ores. Gold grade is, therefore, mainly controlled by vein density. Whereas Fort Knox and Dublin Gulch have similar overall grades, Fort Knox's lower-grade ores are enriched by higher-grade and overprinting, late-stage quartz shear veins. Sheeted vein arrays also occur at deposits such as Brewery Creek (Classic Zone), Dolphin, Shotgun, and Gil, but are not the main ore hosts because each deposit has other features that control grade distribution. Tonnages in the RIRGS are likely to range from 10 to 300 Mt, with grades likely to be from 0.7 to 1.5 g/t Au, hosting approximately 10 to 300 t (0.3–10 Moz) of contained Au. Fort Knox has a resource of about 210 t (7 Moz) of contained Au.

Few of the skarn, replacement, and disseminated deposits within the RIRGS have defined grades and tonnages. The Marn and Horn skarn orebodies in Yukon indicate high

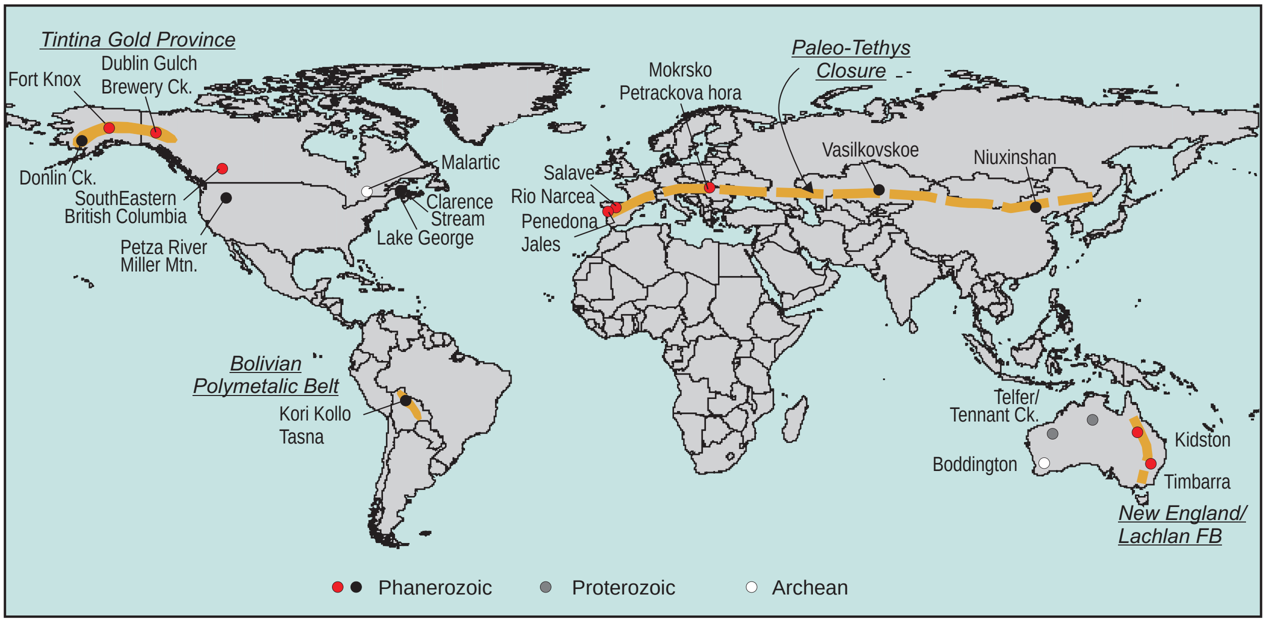

Figure 2. Global distribution of Au deposits suggested to be RIRGS. The Phanerozoic examples, for which there is a high degree of confidence, are shown in red. Ambiguous examples are shown in black, grey, and white. Modified from Thompson et al. (1999), Lang et al. (2000), and Lang and Baker (2001).

grades (8–10 g/t Au), but small tonnages (~50 000–300 000 t). Ryan Lode in central Alaska is the best potential example of an intrusion-related vein, with an average grade of 3 g/t over 3.6 Mt of ore (Bakke et al., 2000) along the margin of a small, unroofed stock. Scheelite Dome represents a huge, although undefined, country rock-hosted RIRGS, with skarn, vein, disseminated, and replacement deposit styles (Hulstein et al., 1999; Mair et al., 2000). Tungsten ores are associated with RIRGS, most significantly is the Ray Gulch deposit (7.26 Mt of 0.87% WO_3), which forms in contact with the Dublin Gulch pluton (Lennan, 1983; Brown et al., 2002).

The epizonal Brewery Creek deposit had an overall grade of 1.44 g/t Au and 17.2 Mt of ore, divided between about eight orebodies, prior to mining and extraction of 9 t (285 000 oz) Au from 1996 to 2002. Parts of some individual orebodies had considerably higher average grades of 4 g/t Au. The overall tonnage of Brewery Creek is misleading because it was explored only for its easily recoverable oxide resource. The underlying sulphide orebody remains undefined, but is the focus of current exploration efforts. The Donlin Creek deposit, at 323 Mt of 2.7 g/t Au and with a Au-As-Sb-Hg signature similar to that of Brewery Creek, had also been suggested to be an epizonal RIRGS (Ebert et al., 2000; Thompson and Newberry 2000), but recent studies (Ebert et al., 2003; Goldfarb et al., 2004) indicate otherwise.

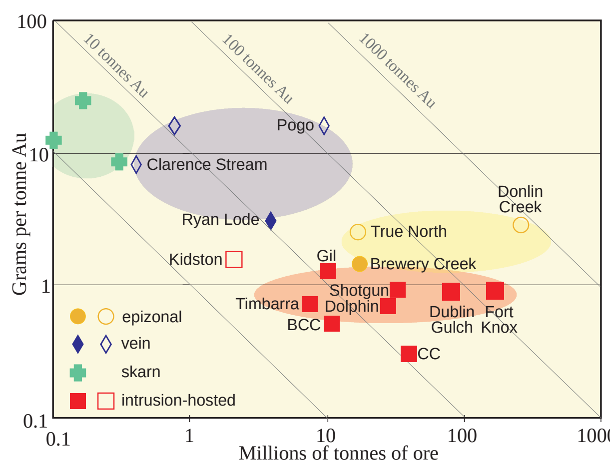

Figure 3. Grade and tonnages of deposits considered to be RIRGS, with emphasis on the intrusion-hosted mineralization style. Other deposit types and controversial deposits are shown for comparison. Open symbols are used for deposits that are controversial. BCC = Brewery Creek Classic zone, CC = Clear Creek.

Geological Attributes

Tectonic Setting and Magmatic Associations

Due to the evolving understanding of this deposit class, and the injudicious incorporation of numerous international examples, the associated tectonic settings are poorly constrained, with back-arc, foreland fold belts, collisional, post-collisional, and magmatic arc settings in orogenic belts having all been proposed (e.g., Thompson et al., 1999; Goldfarb et al., 2000). Examples of widely varying global and generally poorly understood settings for major RIRGS include the Paleo-Tethys sutures, the margins of the North China Craton, the Tasman Orogen, the northern North American Cordilleran orogen, and the Andes (Thompson et al., 1999; Lang et al., 2000; Thompson and Newberry 2000). However, the setting of the best-studied examples in the Tombstone Gold Belt are well understood (Fig. 4; Mair et al., 2006b). Associated RIRGS deposits and occurrences in Yukon are directly related to

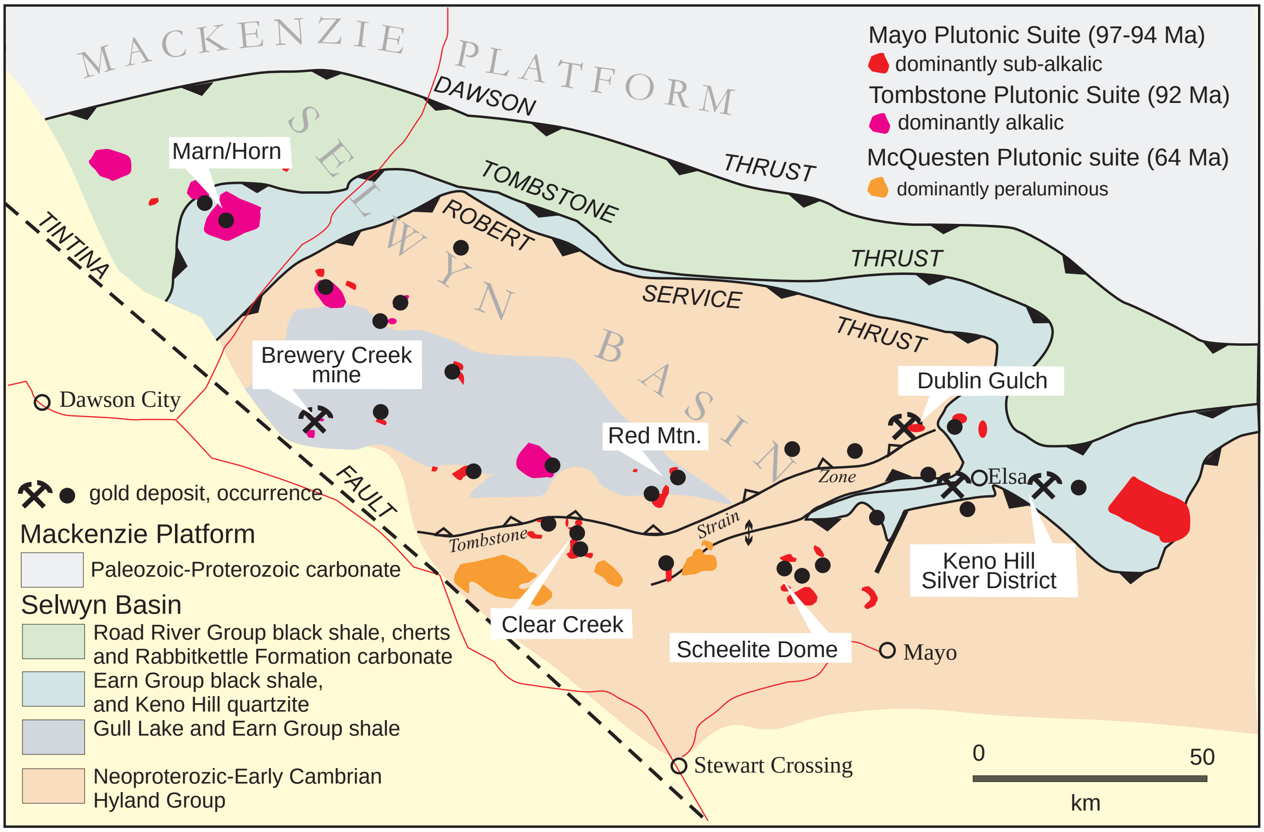

Figure 4. Regional geological setting of the western Tombstone Gold Belt in west-central Yukon. The region is dominated by tectonically thickened Selwyn Basin clastic strata; Mackenzie Platform carbonates dominate north of the Dawson Thrust. Tectonism peaked at ca 105 Ma (Mair et al., 2006b) and was followed by the emplacement of the Mayo Plutonic Suite, then finally by the Tombstone Plutonic Suite, during a period of weak, crustal extension at the end of the mid-Cretaceous. This tectonic and magmatic setting, within variably calcareous and carbonaceous miogeoclinal sedimentary rocks on the cratonic margin far inboard from the subduction-related, continental margin arc, is considered ideal for the formation of RIRGS as well as for W deposits. Modified from Murphy (1997).

specific plutonic suites that were emplaced into tectonically thickened Paleozoic and older miogeoclinal strata that overlie the ancient cratonic margin. The plutons are within the dominantly clastic and locally carbonaceous strata of the Selwyn Basin (Murphy, 1997; Poulsen et al., 1997), and do not occur within the presumably thicker crust of the adjacent carbonate platforms (Fig. 4).

Magmatism has resulted from melts generated and emplaced following Jurassic-Cretaceous subduction, collision, and obduction of outboard terranes that resulted in thickening of the ancient continental margin (Mair et al., 2006a). The associated and resultant plutonic episode that spans 15 to 20 million years formed hundreds of plutons, stocks, dikes, and sills that intruded strata throughout the Selwyn Basin, and related tectonic elements in Alaska. However, those plutons that generated and commonly host the Au mineralization (as well as W mineralization) preferentially belong to the most inboard and youngest of the plutonic suites that together comprise the Tombstone-Tungsten belt (Mortensen et al., 2000; Hart et al., 2004a). These plutons were emplaced during a brief (~5 m.y.) period of weak extension at circa 93 Ma that followed foreland-directed thrusting and crustal thickening, and were the last magmatic response of the mid-Cretaceous Cordilleran orogeny.

Despite suggestions indicating otherwise, the plutons of the Tombstone-Tungsten belt, those associated with RIRGS mineralization, are neither reduced continental “arc” or I-type (Newberry et al., 1995; McCoy et al., 1997; Thompson et al., 1999), nor typical crustal melt-derived or S-type granitoids (Anderson, 1983, 1988; Gordey and Anderson, 1993). They do, however, locally have characteristics of each type. Most have general granitic to monzonitic to granodioritic compositions, are mainly metaluminous, but locally peraluminous, and have some geochemical features similar to calc-alkaline granites. However, many plutons or phases are highly felsic, and have peraluminous compositions with accessory muscovite, tourmaline, and garnet. Other associated plutons are alkaline, mainly potassic, locally with silica undersaturated compositions that are variably enriched in LILEs and HFSEs (Anderson, 1987; Hart et al., 2005) and characteristic of A-type granitoids. The plutons with dominantly metaluminous, peraluminous, and alkalic characteristics define the Mayo, Tungsten, and Tombstone plutonic suites, respectively, and notably, all have associated Au mineralization. The diversity and contrasting features of the various lithologies and the geochemistry of the plutons defies conventional plutonic categorization. Detailed work at Scheelite Dome led Mair (2005) to the construction of a model whereby highly volatile, enriched lithosphere-derived lamprophyric melts interact and eventually mix with ascending and fractionating felsic melts extracted from the lower crust. The result is a wide range of lithological and geochemical characteristics in the associated plutons. The Mayo Plutonic Suite, which has the strongest Au association and affinities with the RIRGS model and includes the Fort Knox and Dublin Gulch plutons, are metaluminous, moderately reduced, moderately fractionated, biotite>>hornblende>pyroxene quartz monzonites (Hart et al., 2005; Mair, 2005)

Therefore, the RIRGS preferentially formed in association with the youngest, furthest inboard, moderately reduced (ilmenite-series) plutonic suite that developed during weak post-collisional extension behind a thickened continental margin. All Yukon, Alaskan, and British Columbia examples are associated with plutons that intruded the ancient continental margin or pericratonic terranes that had been already regionally metamorphosed. A potentially recognizable feature of such plutons may be their paradoxical metaluminous or alkalic character, despite having a highly radiogenic isotopic ancestry that suggests an ancient crustal derivation. The RIRGS-associated plutons in the Yukon and Alaska, even the most metaluminous examples, have high radiogenic initial strontium ratios >0.71 and epsilon Nd values from –7 to –15 (Farmer et al., 2000; Lang, 2001; Mair, 2005; compiled in Hart et al., 2005 and references therein).

Geological Settings and Ore Controls

The RIRGS are best developed in and surrounding the apices of small, cylindrical-shaped plutons that intruded sedimentary or metasedimentary country rocks (Figs. 5 and 6). Intrusion-hosted mineralization is preferentially sited in tensional zones that develop in the pluton's brittle carapace near the country rock contact.

Pluton size is important because batholiths are unlikely to develop into mineralizing systems. The RIRGS are generally well developed, surrounding small (<2 km^2) isolated plutons with mineralization in the intrusion and in the hornfelsed thermal aureole. Larger plutons (2–10 km^2) may have apophyses or later phases that are preferentially mineralized. Roof zones immediately above plutons may also be mineralized, in particular where there is large surface area of contact between the pluton and reactive country rocks.

Pluton geometry is also important. Elongate plutons reflect structural controls on pluton emplacement and indicate a dominant extensional direction that may be important for localizing later mineralization. Cylinder-shaped plutons with steep sides and domed or cupola-like roofs are preferred geometries because these features enhance fluid focusing (Fig. 5). Sharp shoulders also provide regions of structural and rheological contrast that may enhance development of fluid focusing structures (Stephens et al., 2004).

Depth of pluton emplacement may be a feature critical to RIRGS formation. These systems generally lack multidirectional, interconnected vein stockworks that are characteristic of porphyry deposits. This is likely due to their deeper levels of emplacement (5–9 km; Baker and Lang, 2001; Mair et al., 2006a), whereby the increased confining pressure prevents

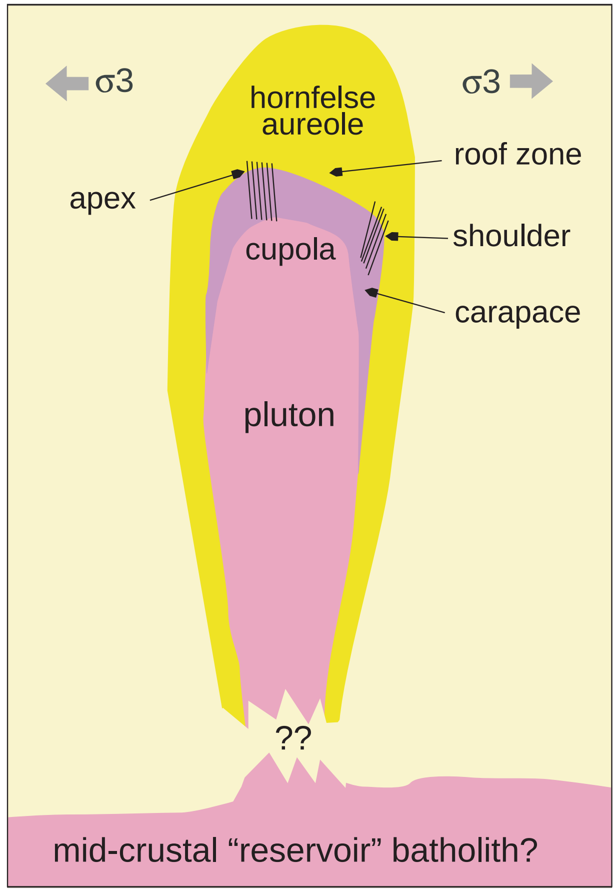

Figure 5. Hypothetical cross section of a small (100 m–5 km across) pluton, probably derived from a larger magmatic reservoir, and intruding into extensional regimes at higher crustal levels. Of note is the asymmetric hornfels aureole and the early-chilled and more brittle marginal carapace. Preferred sites of intrusion-hosted Au mineralization are above the cupola, where exsolved fluids will accumulate, and mineralized fractures developed in the pluton's apex and shoulders. Epizonal styles of mineralization are associated with dike and sill complexes that would be hosted near the top of the hornfels aureole.

rapid fluid exsolution and explosive pressure release, and the development of high permeability stockworks and breccias. As well, the depth precludes the entraining of significant volumes of meteoric water and the formation of broad alteration haloes. As a result, fluid flow and mineralization in most RIRGS systems is largely controlled by structural features that impinge on the thermally driven hydrothermal system (Hart et al., 2000b; Stephens et al., 2000, 2004; Mair, 2005).

The dominant structural control on RIRGS is weak extension that forms arrays of parallel fractures in the brittle carapace that are filled with thin (0.1–5 cm), auriferous, low-sulphide quartz veins that form extensive, intrusion-hosted sheeted arrays (Fig. 7). Hornfels quartzite forms a brittle host lithology for mineralized quartz veins that range from shattered "stockworky" fractures to veins several m in width (O'Dea et al., 2000). Solitary fracture, fissure, and shear-hosted veins occur in the pluton, in the hornfels, and as far as several km from the pluton, and may fill structures that were active while creating space during pluton emplacement (Stephens et al., 2004). At Fort Knox, an economically im-

Figure 6. Looking west into the Fort Knox (Alaska) open pit (July 2004). The light colored rocks are the ca. 92 Ma Vogt pluton that hosts the ore. The deposit is entirely within the exposed part of the pluton, whose top is only barely exposed by erosion as shown by the thin remnant of overlying dark, hornfels country rocks.

portant set of late, through-going quartz-rich shear veins cut through the main part of the intrusion-hosted orebody (Bakke et al., 2000), but controls on their formation are uncertain. Disseminated mineralization may also form near pre-existing structures, which may be older thrust faults. The disseminated deposit style preferentially develops, however, in more epizonal settings where such brittle fractures are more common, hornfelsing is more apparent, and fluid flow is more diffuse.

A final feature controlling mineralization in RIRGS is chemical reactivity of the country rocks (Hart et al., 2000a). Limestone units within the thermal aureole are obvious sites for skarn formation, and the presence of reduced skarns may indicate plutons that are prospective for intrusion-hosted sheeted vein deposits within the larger system. Most associated skarns are scheelite dominant, but they may be overprinted by a lower-temperature Au mineralizing event (Mair, 2005). Hornfelsed, variably calcareous, clastic host rocks are host to auriferous arsenopyrite-rich mineralization, either as replacements, or with diopside ± chlorite ± actinolite skarns that can be widespread, occurring several kilometres away from the causative pluton (Hart et al., 2000a; Mair et al., 2006a).

Deposit Size, Morphology, and Architecture

Areas influenced by fluid interactions from the causative pluton in RIRGS are generally restricted to the limits of the hornfelsed zones, which themselves may extend for as far as 3 km from the pluton's margins. Deposit size and geometry are also dependent on the style of mineralization, and because intrusion-hosted sheeted vein arrays are the most economically significant style, they are preferentially discussed. The Fort Knox deposit is contained within the 1000 m × 600 m surface exposure of the Vogt stock (Bakke et al., 2000). Geometry of the top part of the orebody is controlled by the limits of intrusive rocks, and at depth by cut-off grade that is affected by the density of late, higher-grade shear veins. At Dublin Gulch, there are four zones of sheeted mineralization within the 6 km × 2 km pluton (Fig. 8a). The mineralized zones are on the pluton's shoulders and the largest zone, the Eagle zone, is in the barely unroofed pluton's western margin and in the adjacent country rocks. The Eagle zone covers a surface area of approximately 1000 m × 500 m, has been intersected by drilling at depths of 300 m, and remains open at depth (Smit et al., 1996; Hitchins and Orssich, 1995). The best grades form a shell within a few hundred metres of the pluton's margins, which likely represents the carapace; grades then decrease with depth (Fig. 8b). Similarly, lower vein density and lower grades are indicated at the deeper levels of the Fort Knox orebody.

Elsewhere, sheeted vein arrays are commonly tens of metres wide and hundreds of metres long, and usually entirely within the intrusion, but less commonly in well-developed hornfels zones above the pluton. Within sheeted veins zones, ore grade intersections of at least 3 to 5 veins per metre are best developed near the wallrock contacts, likely due to preferential fracturing of the more brittle, early-chilled pluton carapace, as well as the obvious rheological differences (Stephens et al., 2004).

Intrusion-hosted orebodies may be aligned with the strike direction of extensional fractures that likely result from the same far-field stresses that controlled pluton emplacement and, therefore, may parallel the elongate direction of the pluton. These mineralized corridors are commonly filled with pegmatite, aplite, and lamprophyre dikes.

The epizonal mineralization at Brewery Creek is distal to the causative pluton and occurs in ten orebodies that are distributed over a 12 km-long corridor known as the "reserve trend" (Diment and Craig, 1999; Lindsay et al., 2000). Thick monzonitic sills along this trend are preferentially fractured compared to surrounding carbonaceous shales, and they host most of the ore. Individual orebodies are generally a few hundred metres long. The thickness of most of the orebodies is uncertain, because most were only explored to their limits of oxidation (~30 m); however, recent drilling indicates locally high-grade sulphide ores at greater depths (e.g., 6.8 g/t Au over 15.3 m at 70 m depth; Alexco Resources Corp., 2006).

Ore Paragenesis, Mineralogy, and Zonation

The ore paragenesis, mineralogy, and related zonation is controlled by the temperature of fluids during mineral deposition and fluid-wallrock interactions. As such, the ore stages define various metal assemblages that vary in time and space, are well developed with their distance away from the causative pluton, and change according to the nature of the country rocks. Within the paragenesis, the earliest ore stages as characterized by Brown et al. (2002), and Mair et al. (2006b) are within skarns developed on the pluton's margins. Features of vein paragenesis are illustrated schematically in Figure 9 and are summarized below from the work of

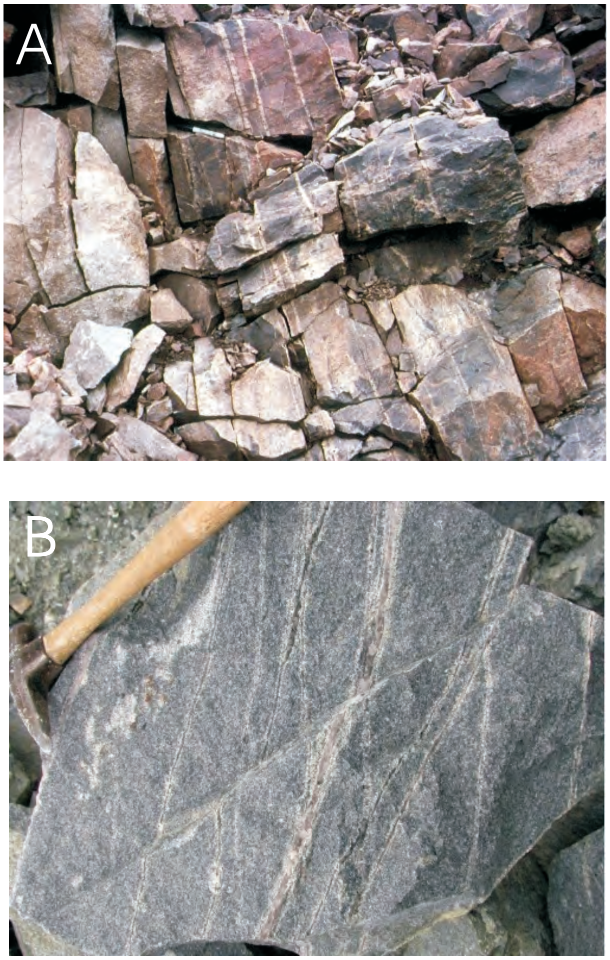

Figure 7. (A) Outcrop-scale exposure of an array of intrusion-hosted, sheeted quartz veins in the apex of the Rhosgobel pluton at Clear Creek, Yukon. One- to three-cm-wide veins of simple, single-stage quartz with minor sulphides and scheelite fill parallel, extensional fractures that may extend for hundreds of metres. Individual veins may contain 50 g/t Au, but host rocks are barren such that vein density is the grade-controlling feature. Wide intersections generally average 1 g/t Au. Note 14 cm-long marker pen (circled in red) for scale. **(B)** Ore from Fort Knox i s dominated by a series of subparallel, white and grey, single-stage quartz-sulphide veins that are parallel with the east–west elongate direction of the pluton, and other structural elements such as dikes and shears (in this photo, the veins are offset by a small fracture). It should be noted that there are not interconnected, multidirectional quartz vein stockworks that are typical of porphyry deposits. Alteration, mainly sericite-calcite, is limited to the immediate vein selvages.

many authors, including Maloof et al. (2001), Marsh et al. (2003), and Mair et al. (2006b).

Early ore stages are dominated by high-temperature (650°C) anhydrous diopsidic pyroxene-plagioclase skarns that locally contain scheelite. Lower-temperature (420°C), and sometimes overprinting, hydrous, either biotite-, zoisite-, or actinolite-dominant skarn assemblages may be Au-bearing where they contain significant amounts of sulphide minerals. High-temperature sulphide assemblages are dominated by pyrrhotite>>chalcopyrite, but lower-temperature assemblages are dominated by arsenopyrite with various Bi-Te-Sb-Pb-Au minerals and alloys (Fig. 10). All silicate assemblages lack garnet, which is a feature of reduced skarns (Meinert, 1998).

Early veins are dominantly intrusion-hosted and are characterized by alkali feldspar-, mica-, and scheelite-bearing quartz veins that may host only sparse sulphide minerals and may lack Au. Slightly lower-temperature, sheeted vein arrays are similar but may host up to a few percent pyrite or arsenopyrite, but with blebs of various Au-Bi-Te alloys, and are the key hosts to Au mineralization. At the system scale, and more commonly outside of the intrusion, are more sulphide-rich arsenopyrite and antimony veins. The last gasps of the hydrothermal event generate Ag-Pb-Zn-bearing quartz veins which occur in the most distal locations, often beyond the limits of the hornfelsed aureole. These distal Ag-rich galena-sphalerite quartz-carbonate veins also form the 30 km-long Keno Hill Ag district and may indicate a regional zoning within the Tombstone Gold Belt.

The mineralogy of intrusion-hosted sheeted veins, such as those at Dublin Gulch and Fort Knox, comprise a single stage of massive, translucent grey or white quartz, locally with subordinate coarse-grained, white K-feldspar or mica that are most commonly on the vein margins. Some veins are "dry", lacking quartz, and consist of sulphide mineral-coated fractures with biotite, which form a limonitic gouge where oxidized. Low sulphide contents (0.1%–2%) typify intrusion-hosted assemblages, which are dominated by pyrite > pyrrhotite > arsenopyrite with accessory scheelite and bismuthinite. Arsenopyrite is much more abundant in country rock-hosted veins (up to 10 vol.%), and is common with pyrrhotite in replacement-style mineralization. Accessory molybdenite occurs locally in thin quartz veins; chalcopyrite, sphalerite, and galena are sparse. Cassiterite has been reported near some occurrences (e.g., Tin Dome at Dublin Gulch) but is rare and does not occur with Au.

Native Bi and Bi-bearing sulphosalt minerals are commonly described from various mineralization styles in RIRGS. They occur late in the paragenesis and are typically alloyed with Te, Pb, Sb, or Au. Tellurobismutite, maldonite, tetradymite, native Bi, boulangerite, and Bi-Pb sulphosalts have been recognized at Fort Knox (McCoy et al., 1997, 2002). At Dublin Gulch, approximately 40% of the Au occurs as complex intergrowths with native Bi (Hitchins and Orssich, 1995), but Au also occurs in Bi-Pb sulphosalts with galena and molybdenite (Maloof et al., 2001), and with bismuthinite, tetradymite, tellurobismuthite (Hitchins and Orssich, 1995). The common association of very high fineness free Au within or adjacent to native Bi or bismuth-bearing minerals suggests that Au may have exsolved from earlier, high-temperature Bi-alloys, upon cooling (Fig. 10).

Ore mineralogy at the epizonal Brewery Creek deposit is distinctly different but relatively simple. It is dominated by early pyrite, with associated arsenian pyrite and arsenopyrite (Diment and Craig, 1999; Lindsay et al., 2000). Oxidized mineralization appears disseminated with limonite, but hypogene ore shows sulphide minerals in, and adjacent to, spaced, sulphidized fractures lacking quartz. Gold is refractory, being associated with acicular arsenopyrite and the arsenian pyrite overgrowths on early pyrite. Although late stibnite veins are also a common feature, their association with Au is equivocal.

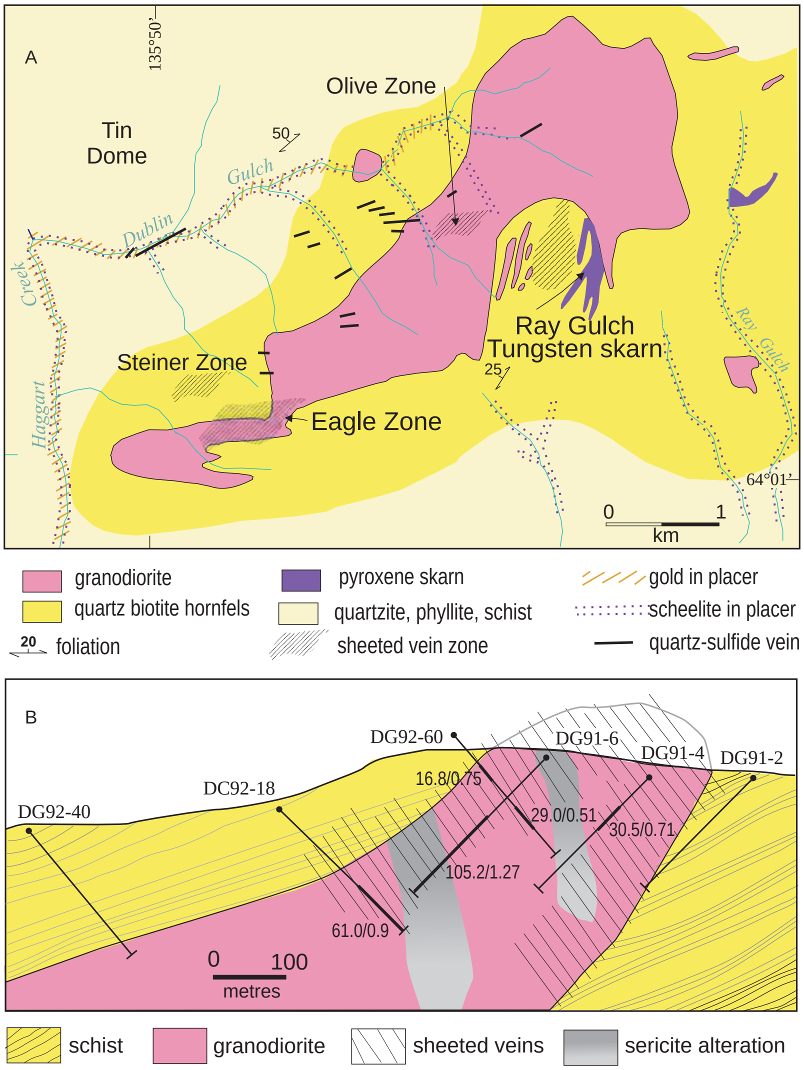

FIGURE 8. **(A)** The Dublin Gulch pluton is a good example of a RIRGS with many different styles of mineralization, including intrusion-hosted sheeted vein arrays, scheelite-bearing skarns, tin greisens, Au- and arsenopyrite-bearing quartz veins, and creeks with placer Au and scheelite. Bismuthinite has also been found in the placer concentrates. Beyond the limits of this figure, and the hornfels zone, Ag-Pb-Zn-bearing quartz veins also occur. **(B)** Cross section of the Eagle zone at the west end of the Dublin Gulch pluton. Sheeted vein arrays are shown schematically but are mostly concentrated in the margins of the apical region of the pluton and do not appreciably occur in the adjacent, less-competent wall rocks. Modified from Smit et al. (1996), with drill intersections (given as metres/grams per tonne Au) from Hitchins and Orssich (1995).

Geochemical Features

The RIRGS are geochemically distinguished from oxidized intrusion-related mineralizing systems by their dominance in Au, associated W, and lack of anomalous Cu. Tungsten enrichments and deposits occur within the RIRGS, such as the Ray Gulch W skarn at Dublin Gulch, but Au and W enrichments may be spatially distinct (Brown et al., 2002), or later Au may overprint early W veins or skarns (Mair et al., 2006a). Bismuth and Te are common elements but are also characteristic features of many other deposit models.

Sulphide-rich (10%) sheeted veins at Clear Creek contain up to 30 g/t Au, as much as 1 wt.% As, and 100 to 1000 ppm Bi and W (Marsh et al., 1999). At Fort Knox, Au strongly correlates with Bi and Te, and but weak enrichments of W, Mo, Sb, and As do not correlate with elevated Au (Bakke, 1995; Flanigan et al., 2000). High Au grade intersections at Dublin Gulch have elevated Bi, As, Sb, Cu, and Zn concentrations, although again Au grades solely correlate with Bi (Maloof et al., 2001) and probably with Te, but such data are unavailable. Factor analysis on the Clear Creek veins indicated a dominant Au-rich As-Au-Bi±Sb,Te element association, and a base metal suite of Ag-Bi-Pb±As, Au that represents a cooler/later assemblage (Marsh et al., 1999). Tungsten displays little correlation with either element suite, but had values of >300 ppm in many Au-rich samples. Similarly, mineralization at Scheelite Dome was characterized by both a Au-Te-Bi±W±As and a Ag-Pb-Zn-Cd-Sb±Cu±Au elemental association, with the latter characteristic of ores in the nearby Keno Hill Ag district (Mair et al., 2000).

Epizonal Au at Brewery Creek lacks the typical W, Bi, and Te association. Instead, Au ores occur with arsenopyrite and are, therefore, dominated by As. Late fractures host stibnite enrichments but Au-Sb correlations are erratic. Additionally, Hg was recovered during mining, thus giving Brewery Creek an As-Sb-Hg association.

Geochemical zoning occurs at the pluton scale, with elemental zonation reflecting the cooling trend of the hydrothermal fluids, with a component of country-rock buffering. The pluton's geochemical influence is typically on the order of 1 to 3 km, but can be larger in roof zones above the pluton, for example >10 km at Scheelite Dome. Intrusion-hosted ores are dominated by a Au-W-Bi-Te signature with Au correlating well with Bi and Te, but not at all with W (Fig. 11). Geochemical signatures of high-temperature skarns adjacent to the pluton may be similar, but in some systems, As and W enrichments may be more significant than Bi-Te signatures. Percent-level Cu and Bi, with 8.6 g/t Au at the Marn deposit (Brown and Nesbitt, 1987), occur only in skarns formed from alkalic or more oxidized plutons. Hornfels-hosted ores, which may be veins, disseminations, or replacements, are more sulphide-rich than intrusion-hosted ores, and are characterized by elevated As that correlates with Au (Flannigan et al., 2000). Distal mineralization, which forms at or beyond the limits of hornfels, is dominated by a Pb-Ag-Zn or Sb-rich geochemical association, and typically occurs as fault-filled veins.

Vertical zonation patterns within a system may mimic the lateral zonation, but may be less evident due to the much broader thermal gradients that occur above the pluton. Mineralization or entire orebodies (e.g., Gil in the Fairbanks

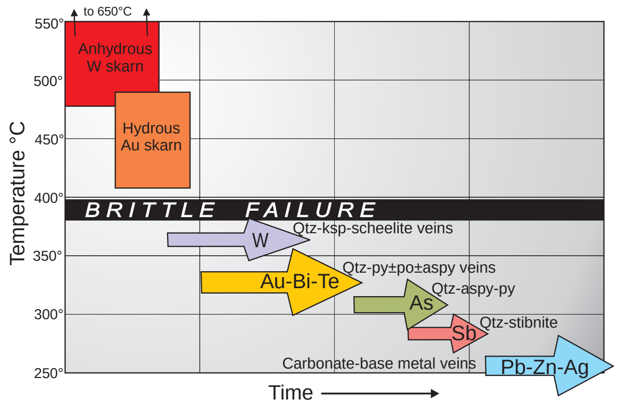

Figure 9. Schematic paragenesis of evolving types and metal associations of mineralization in typical cooling RIRGS. As well as time, the lower axis could also represents distance away from the fluid source such that As-, Sb- and Ag-P-Zn veins are almost exclusively beyond the causative pluton.

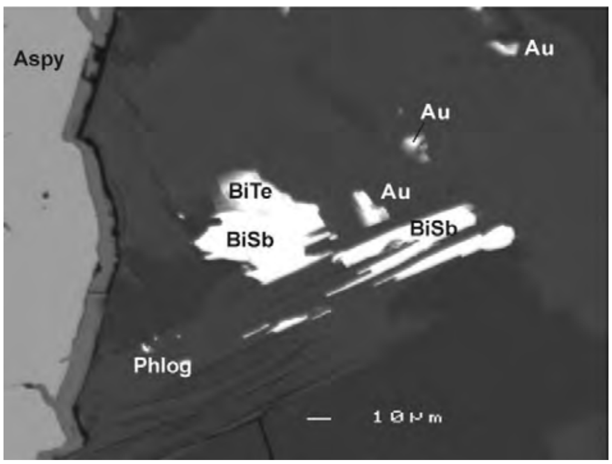

Figure 10. SEM backscatter image of Scheelite Dome Au-W-As-Bi skarn (Tom zone), emphasizing the occurrence of Bi-Te-Sb alloys and Au. Gold occurs as small, 5 to 20 micron particles near larger Bi-Te-Sb alloys that occur as intergrain infillings. Gold may be deposited in high-temperature alloys and exsolved out upon cooling. This sample contains 17 g/t Au, 12 ppm Te, 426 ppm Bi, 161 ppm W, and 3300 ppm As. Gold in vein-hosted ores has a similar character and metal tenor. Figure and data courtesy of John Mair.

area) may be within a roof zone altered to hornsfel above unexposed plutons, which may be several kilometres below and fail to show apparent zoning trends. Within the pluton, suggestions of W or Mo enrichments at depth (Bakke, 1995) have not been supported by data, but decreases in Au grades with depth are evident at Fort Knox. A key aspect of vertical zonation within RIRGS are the more apparent variations within shallowly emplaced systems. The Brewery Creek deposit and nearby occurrences (Ida, Oro) emphasize that the fluid systems associated with these more shallowly emplaced systems (~3 km) take on epizonal characteristics and metal signatures in response to the lower temperatures.

Alteration Mineralogy and Fluid Geochemistry

Alteration in intrusion-hosted ores is neither extensive nor intensive, and is typically limited to 0.5 to 3 cm-wide selvages adjacent to the veins with intervening, apparently

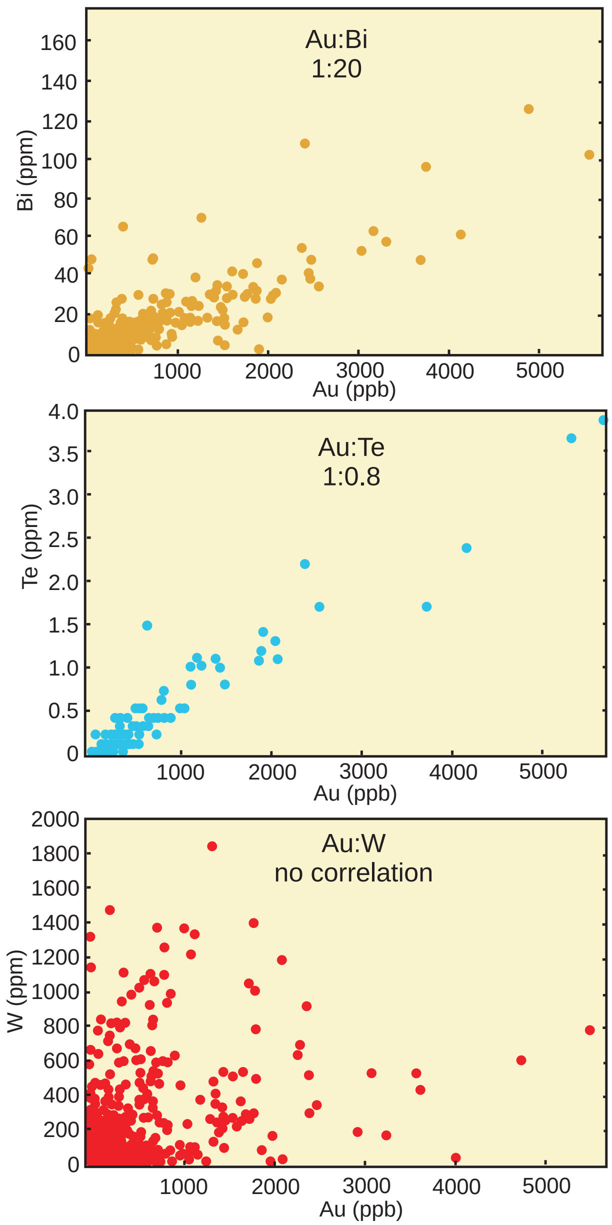

Figure 11. Binary element plots of intrusion-hosted ores dominated by sheeted veins that demonstrate a Au-Bi-Te-W association. Gold displays a high positive correlation with Bi and Te, but not with W. These data are from the Rhosgobel zone at Clear Creek (Yukon); each point represents the analysis of 1.5 m of drill core. Note that there are fewer analyses for Te.

fresh, barren rock (Fig. 7B). Alteration proximal to veins most commonly consists of either texture-destructive K-feldspar replacement (Maloof et al., 2001) or pervasive carbonate replacement of mafic minerals. An adjacent sericite-dominant ± pyrite ± carbonate assemblage overprinting plagioclase and mafic minerals is common. In particular, this alteration distinguishes Au-bearing from (higher-temperature?) non-Au-bearing veins at Fort Knox (P. Jensen, pers. commun., 2002). Chlorite alteration may be more distal, but is not pervasive throughout the host rocks. Vein-proximal alteration may be cryptic and more easily observed on weathered surfaces. Alternatively, alteration of country rocks surrounding a causative pluton may be both intensive and extensive. Although typically dominated by prograde alteration to biotite-quartz ± pyrrhotite hornfels, later retrograde fluid-dominated alteration may be widespread. For example, sericite after biotite may occupy large regions of the hornfels aureole, such as at Scheelite Dome (Mair et al., 2000), and is also a more focused feature of distal Ag-Pb-Zn veins in the Keno Hill district (Lynch, 1989). At the epizonal Brewery Creek deposit, PIMA (Portable Infrared Mineral Analyser) studies indicate that hypogene ores contain illite surrounded by a more extensive ankerite alteration halo (R. Diment, pers. commun., 2001).

The fluid chemistry of the intrusion-hosted sheeted veins of Yukon deposits has been well documented by Baker and Lang (2001), Baker (2002), Marsh et al. (2003), and Mair et al. (2006). Most Au-W-Bi-Te veins consist of early high-temperature (380°–300°C), CO_2-rich (5%–14%), low-salinity (2–6 wt.% NaCl equiv.) aqueous carbonic fluids with CH_4 and N_2. These fluids cooled and locally unmixed to yield lower temperature (mostly 280°–250°C, but as low as 160°C), immiscible, low-salinity (0.2 wt.% NaCl equiv.) and high-salinity (6–15 wt.% NaCl equiv.) aqueous fluids lacking significant CO_2, which formed the As-, Sb-, and Ag-Pb-Zn veins. In alkalic magmatic systems that have associated Cu mineralization, such as Mike Lake and Emerald Lake, the fluids evolved to become highly saline with 30 to 55 wt.% NaCl equivalent. Skarns and veins interacting with country rocks have elevated CH_4, which likely results from interactions with the sedimentary rocks causing more evolved fluids to become increasingly reduced (Mair et al., 2006a). In epizonal systems such as Brewery Creek, the fluids are aqueous and lack CO_2, but are characterized locally by high salinities. Fluid inclusion barometry indicates Au deposition at most sites (Dublin Gulch, Clear Creek, Scheelite Dome) at depths of 3 to 9 km (mostly 5–7 km).

Comprehensive light stable isotopic studies of oxygen and sulphur have been undertaken at the Clear Creek (Marsh et al., 2003) and Scheelite Dome (Mair et al., 2006a) systems. The $\delta^{18}O_{quartz}$ of the Au-W-Bi-Te sheeted quartz veins range from 14 to 16 per mil, slightly heavier than the host granitic rocks at 11 to 13 per mil, and similar to values of 13 to 16 per mil for host sedimentary rocks. Antimony and Ag-Pb-Zn veins hosted by country rocks have $\delta^{18}O$ values of 17 to 20 per mil reflecting extensive wall-rock interaction. Sulphur isotope data display values of 0 to –3 per mil for intrusion-hosted quartz Au-W-Bi-Te veins, 2 to –7 per mil for various skarn mineralization, –7 to –10 per mil for country rock-hosted arsenopyrite veins, and –9 to –11 per mil for Ag-Pb-Zn veins. Like the oxygen isotope and fluid inclusion data, the $\delta^{34}S$ values indicate a trend that reflects progressive interaction with sedimentary country rocks as the hydrothermal system evolves and cools. Therefore, in addition to phase separation, progressive cooling and reduction of the fluid were likely mechanisms of Au deposition (Mair et al., 2006a).

Empirical and Genetic Exploration Models

Empirical Model

A schematic empirical model for RIRGS (Fig. 12) incorporates observable features from the "type" deposits and occurrences in the Yukon and Alaska. The key empirical features have been described above, but those features that are considered as critically distinguishing attributes are listed below.

System

Mineralization extends beyond the limits of the intrusion, and locally beyond the thermal aureole yielding a broad mineralizing system (Fig. 8A). The size of the system is generally dictated by the limits of the thermal aureole, commonly several kilometres across, but can be dependent on the depth of erosion with the broadest and best developed mineralization at the top of or above the pluton (Fig. 5).

Diverse Mineralization

Differing styles of mineralization emphasize not only the extent of the mineralizing system, but also the involvement of the country rock and its role in creating mineral system diversity. Chemically reactive and/or physically brittle sedimentary strata result in a diversity of mineralization styles, whereas the causative pluton is typically dominated by solely sheeted vein sets.

Zoned Deposit Types

RIRGS typically deposit metals in intrusion-hosted, contact, pluton-proximal, and pluton-distal settings, and thus exhibit a predictable zonation of differing deposit styles outward from the central, mineralizing pluton (Fig. 12). Skarns and replacements are generally pluton proximal, with an increase in structural control on more distal mineralization. There is also crustal-scale vertical zonation, with epizonal occurrences forming at shallower levels.

Concentric Metal Zoning

Predictable metal signatures develop broad-scale zoning surrounding and above a central causative pluton, due primarily to the effects of steep thermal gradients on fluid chemistry (Figs. 9, 12). Gradients and metal zones are steeper on the sides of the pluton and broadly developed above it (Fig. 5). Zoning is somewhat analogous to that identified in porphyry systems (e.g., Jones, 1992).

Metal Associations

Gold, as well as W, may form ore, but Au does not directly correlate with W (Fig. 11). Bismuth and Te are enriched in intrusion-hosted Au ores and correlate with Au. Arsenic enrichments characterize hornfels-hosted mineralization and form regional-scale geochemical anomalies.

Pluton Features

Associated plutons are generally small and solitary, with "smoking gun" characteristics that indicate they were the source of the hydrothermal fluids. Features that provide evidence of high volatile contents, fractionation, and fluid ex-

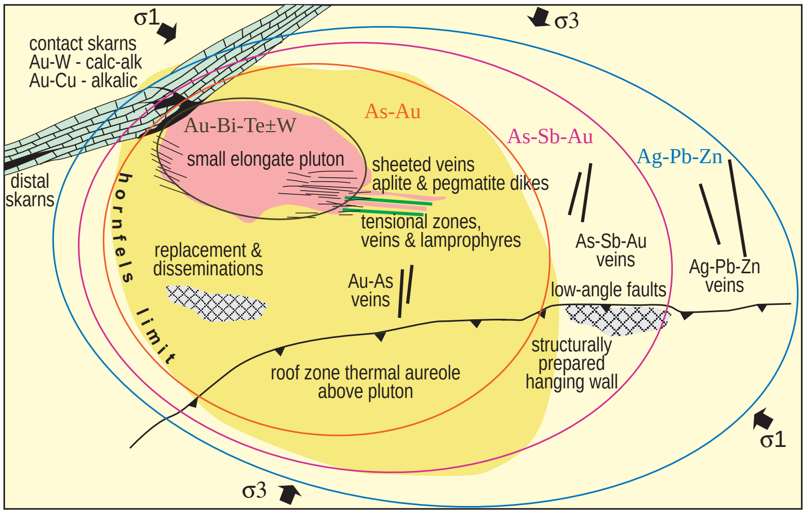

Figure 12. General plan model of RIRGS from the Tintina Gold Province. Of note are the wide range of mineralization styles and geochemical variations that vary predictably outward from a central pluton. Scale is dependent on the size of the exposed pluton, which is likely to range from 100 m to 5 km in diameter. Modified from Hart et al. (2002).

solution include the presence of hornblende in biotite granitoids, textural and grain-size variations, aplite and pegmatite dikes, tourmaline veins, miarolitic cavities and vugs, greisen-style alteration, unidirectional solidification textures, and cupola-hosted mineralization (Fig. 13).

Redox State

The RIRGS are associated with felsic, ilmenite-series plutons that lack magnetite and, as such, have low magnetic susceptibilities, low ferric:ferrous ratios (<0.3), and flat aeromagnetic responses. Associated mineralization has a reduced character, with pyrrhotite commonly the dominant sulphide mineral and fluids that may locally contain methane.

Genetic Model

The RIRGS genetic model requires that the ore-generating cooling pluton reaches volatile saturation and that a fluid exsolves from the melt. Metals and volatiles such as sulphur and halogens presumably preferentially partition from the melt into an exsolving aqueous-carbonic ore fluid phase. Pressure, or depth of emplacement, exerts the greatest control on volatile saturation, particularly because volatiles are easily dissolved in felsic melts under higher pressures (Burnham and Ohmoto, 1980). However, volatile saturation is also induced by magmatic processes such as fractional crystallization, magma mixing, or simple cooling. Pluton emplacement depth appears, therefore, to be critical and explains why RIRGS are typically associated with a specific suite of plutons distributed over a broad area; such plutons likely represent melt crystallization at the same general crustal level.

At the pluton scale, mineralization is limited to regions above and outward from the site of volatile saturation. Being less dense than the melt, fluids will migrate to the uppermost parts of the less viscous portion of the magma chamber, which is usually the volatile-rich magmatic cupola immediately under the earlier-formed carapace (Candela and Blevin, 1995). Fluids will invade fractures in the carapace and opportunistically leak into and react with adjacent country rocks. Mineral occurrences are, therefore, most commonly sited at the pluton's apex, in the igneous carapace, or in hornfelsed country rocks adjacent to and above the pluton. The host plutons to many RIRGS likely have magma volumes that are too small to provide the large amount of metals and volatiles contained in these deposits, thereby suggesting the participation of larger volumes of primary magmatic fluids and metals (Candela and Piccoli, 2005). These could include deeper unexposed batholiths or mafic lamprophyric melts.

The metallogeny of mineral deposits associated with intrusive rocks is mainly controlled by the associated magma's primary oxidation state (Ishihara, 1981) and the degree of magma fractionation (Thompson et al., 1999; Fig. 14). Highly oxidized magmas in arc environments that are relatively unfractionated will have a metal tenor dominated by Cu and potentially Au. In reduced magmatic systems, Cu is likely stripped out by the early precipitation of sulphide melt blebs, whereas W behaves incompatibly and, therefore, is enriched during fractionation. Tungsten is relatively easy to mobilize in reduced, CO_2-rich hydrothermal systems. Controls on the partitioning of Au in evolving magmatic systems is poorly understood, but empirically it is associated with and enriched in both highly oxidized and moderately reduced systems (e.g., Leveille et al., 1988; Rowins, 2000; Mungall, 2002); in the latter case, this may lead to formation of a RIRGS.

Knowledge of magmatic fluid physical and chemical properties for most intrusion-related mineral deposits was originally based on comparison with the porphyry model that emphasized the role of highly saline aqueous fluids in metal transport under oxidized magmatic conditions (e.g., Burnham, 1979). The RIRGS are, however, dominated by aqueous carbonic fluids that have high volumes of CO_2 and low salinities, are largely reduced, and only locally contain highly saline fluids (Baker and Lang, 2001; Marsh et al., 2003; Mair et al., 2006b). These fluids are unlike those in porphyry Cu deposits.

The concentration of metals through magma fractionation have been suggested by McCoy et al. (1997) for the Alaskan RIRGS and was shown to occur in the more siliceous Timbarra system of eastern Australia (Mustard et al., 2006). Conversely, Mair (2005), working in Yukon, has suggested that input of volatile-rich mafic magmas were likely responsible for volatile enrichment that assisted the early, less-volatile, siliceous magmas in reaching fluid saturation. It is uncertain but probable that this mixing also played a role in metal enrichment as well.

Because an underlying feature of the RIRGS classification is the direct genetic association of mineralization with a causative magma, geochronology is of fundamental importance in processes studies. Many lines of evidence suggest that

Figure 13. Vug in the Fort Knox pluton filled with coarse-grained quartz, feldspar, and (chloritized) amphibole. Features such as this indicate that the pluton reached fluid saturation and exsolved a hydrothermal fluid. A pluton's response to high volatile contents is the formation of pegmatitic and aplitic dikes as well as a mineralizing fluid.

these magmatic systems cool quickly, indicating that magmatic and hydrothermal processes must be essentially coeval. Comparative geochronology on magmatic and hydrothermal phases using different analytical methods indicates that an entire magmatic-hydrothermal system can be discerned to within a 2 to 3 million year window (Selby et al., 2001; Hart et al., 2004b).

Key Exploration Criteria

At the regional scale, exploration should focus on the foreland parts of orogenic belts where felsic plutons have intruded ancient continental margins, inland of accreted terranes or collisional zones. These regions may be historically better recognized for their W or Sn metal tenor, and may also host Ag-rich veins or Au placers that are associated with the plutons. All mineralizing plutons that belong to the same suite or time interval are potential targets for RIRGS. Prospective plutons were preferably intruded deeper than ~5 km to keep these low-volume hydrothermal systems contained in the melts and subsequently focused during exsolution. RIRGS associated with shallower plutons are characterized by more diffuse epizonal styles of mineralization and a Au-As-Sb-Hg signature. Associated plutons will have low primary oxidation states and are, therefore, easy to differentiate from magnetite-series plutons of true continental margin arcs that have associated Cu-Mo porphyry deposits.

At the deposit scale, targeting the pluton's carapace is critical such that those plutons that are barely unroofed are considered the best locations for RIRGS. Roof zones above plutons are also highly prospective, but may be difficult to target as they are rarely noted on geological maps. Deeply eroded plutons, recognized by their large circular-shaped surface areas, are unlikely to yield large-tonnage intrusion-hosted sheeted vein deposits, but may nevertheless have hornfels with Au-bearing skarns or veins. Understanding the structural controls on pluton emplacement may be key to developing targets and preferred deposit orientations within a magmatic-hydrothermal system (Stephens et al., 2004). Additional exploration techniques and exploration pathways to discovery are described in Hart et al. (2002).

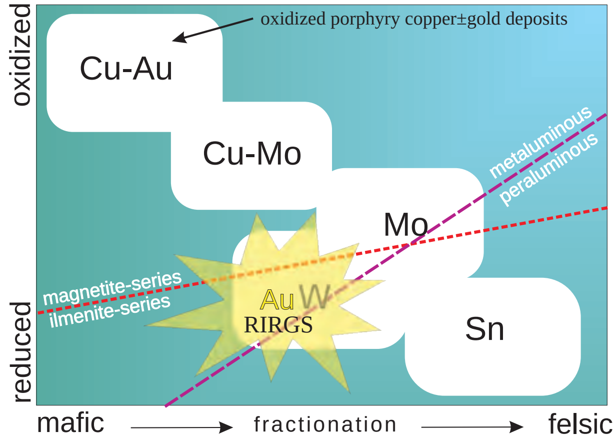

Figure 14. Schematic plot emphasizing the variations in metal association as a function of the primary magmatic oxidation state and the lithologic character of the associated plutonic rocks. Gold, associated with RIRGS plot in the field occupied by W systems but notably is far removed from the more characteristic Au-Cu field that is associated with highly oxidized and more mafic magmas. The result is that Au can be enriched in both oxidized and reduced magmas, but that a reduced oxidation state may be necessary for Au enrichment in fractionated systems. The corollary is that fractionated oxidized systems are likely to be depleted in Au. Modified from Thompson et al. (1999).

Geochemical

Regional geochemical surveys are very good at identifying mineralizing plutons, particularly where characterized by broad As aureoles, such as those of the Tombstone Gold Belt (Fig. 15). Placer Au may occur in related drainages in significant amounts (>100 000 oz; e.g., Allen et al., 1999). Placer scheelite is also a feature of many occurrences. Soil geochemistry can be extremely effective locally at delineating potential mineralization within the area of a causative pluton, and recognizing mineralized portions of its hornfelsed zone (e.g., Diment and Craig, 1999; Hulstein et al., 1999). Soil lines should cross the extensional direction that may mimic a pluton's elongation direction. Gold grades can be up to several grams per tonne in some soils, but low anomaly thresholds (25 ppb Au) may be required for surveys with low geochemical response (Diment and Craig, 1999). Anomalous Bi, Te, or W values, or multi-element analyses using metal ratios or factor analysis can assist in interpretation of vein types or predicting more proximal (i.e., intrusion-hosted) ores in areas with poor rock exposure (Marsh et al., 1999; Mair et al., 2000).

Geophysical

Geophysical methods that identify Au mineralization in RIRGS are still elusive, but potential-field methods are ideal at assisting interpretations of geological settings where ores could be found. Regional aeromagnetic surveys are effective at identifying unmapped or unexposed plutons or locating roof zones (Fig. 16). Associated plutons have low magnetic responses; however, pyrrhotite concentrations in hornfelsed aureoles may yield doughnut-shaped signatures for exposed plutons and simple bulls eyes for roof zones of unexposed plutons (Hart et al., 2002). This response is pronounced in reducing sedimentary rocks where pyrrhotite formation is

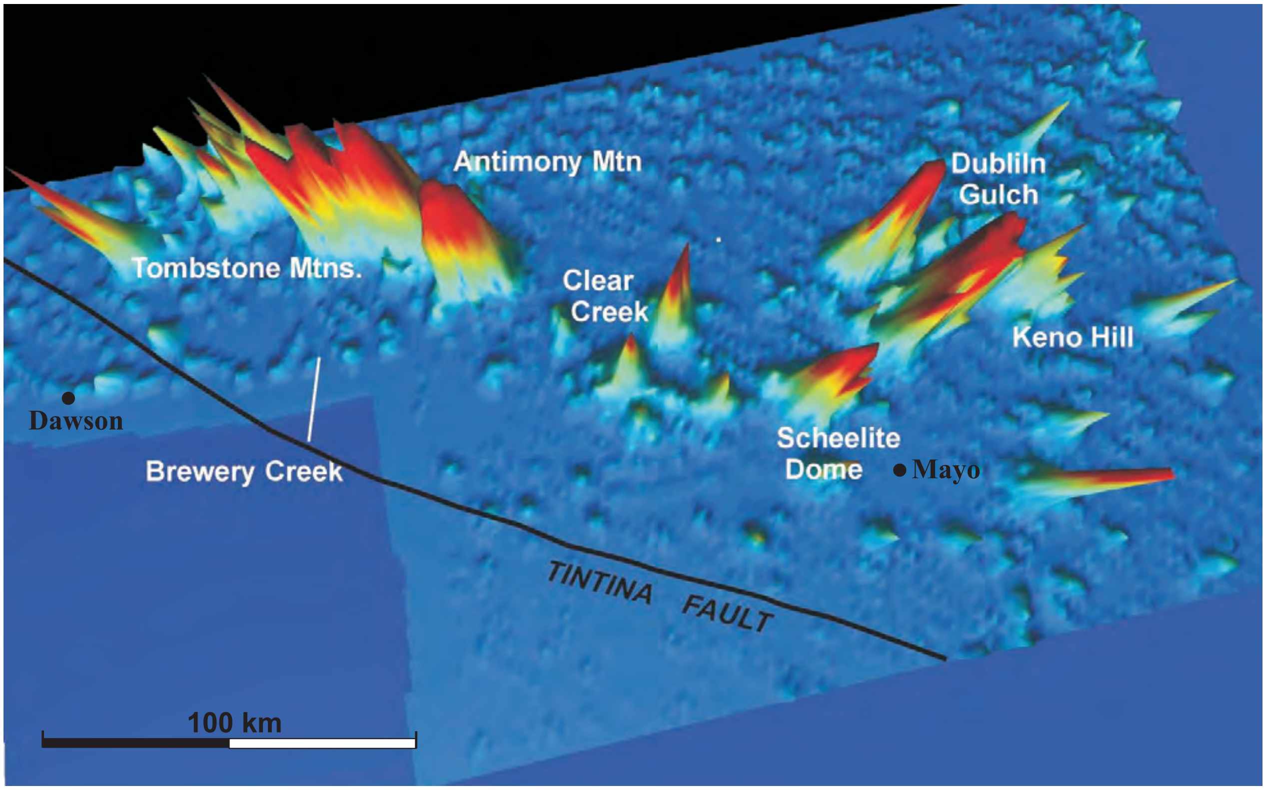

FIGURE 15. Gridded and contoured regional stream silt geochemical data for arsenic for the west-central Yukon. Sample density is one per 13 km². Background values are <50 ppm As, and regions in red have values >500 ppm As. Data are compiled from Geological Survey of Canada open file reports (Geological Survey of Canada, 1978, 1990, 1991). Despite the dominance of arsenopyrite in the Brewery Creek orebodies, note the absence of a significant As anomaly for this poorly exposed property.

more likely but otherwise may be lacking.

Within intrusion-hosted systems, geophysical exploration methods have largely yielded ambiguous to poor results (Bakke, 1995). Within the hornfelsed aureoles, however, magnetic methods allow identification of major structures as lows produced by alteration of pyrrhotite. Induced polarization methods are useful for identifying reactive and sulphidized zones within the hornfels when targeting disseminated-, replacement-, or skarn-type ores (M. Powers and G. Carlson, pers. commun. 1999).

Knowledge Gaps

- This evolving RIRGS classification suffers from nomenclature issues and there is a need for a framework for all intrusion-related deposit models to emphasize distinguishing characteristics (Hart, 2005). In particular, there is uncertainty about the inclusion of many of the variants of intrusion-related mineralization styles (e.g., epizonal, veins), as well as other global or Archean examples, which result in considerable uncertainty in this deposit classification.

- Knowledge gaps identified by Thompson and Newberry (2000), and Lang and Baker (2001) emphasize the need for improved basic deposit descriptions and focused research on individual systems. Despite a good geological overview of the most significant recognized RIRGS (Bakke, 1995; Bakke et al., 2000), Fort Knox remains among the most poorly studied and understood example. In contrast, Dublin Gulch (Hitchins and Orssich, 1995; Maloof et al., 2001), Scheelite Dome (Mair, 2004; Mair et al., 2006b), and Clear Creek (Marsh et al., 2003; Stephens et al., 2004) have all seen more focused studies.

- Many critical questions still need to be answered. What features of a causative pluton's magmatic character are important in the formation of RIRGS? Are the Tombstone Gold Belt plutons unique? Why are these deposits not more common in similar tectonic settings elsewhere, or in Precambrian rocks?

- The controlling features of most of the ore-forming processes, such as metal enrichment and volatile saturation remain poorly understood, and knowledge gaps are nearly identical to those identified by Sinclair (2007) for porphyry deposits associated with oxidized magmas. More specific to RIRGS, however, is the role of oxidation state on controlling Au concentration in magmatic systems.

- There is controversy about the most appropriate model for many Au deposits; in particular, the Pogo and Donlin Creek deposits of interior Alaska have been interpreted as both RIRGS (Smith et al., 1999; Ebert et al., 2000; Rhys

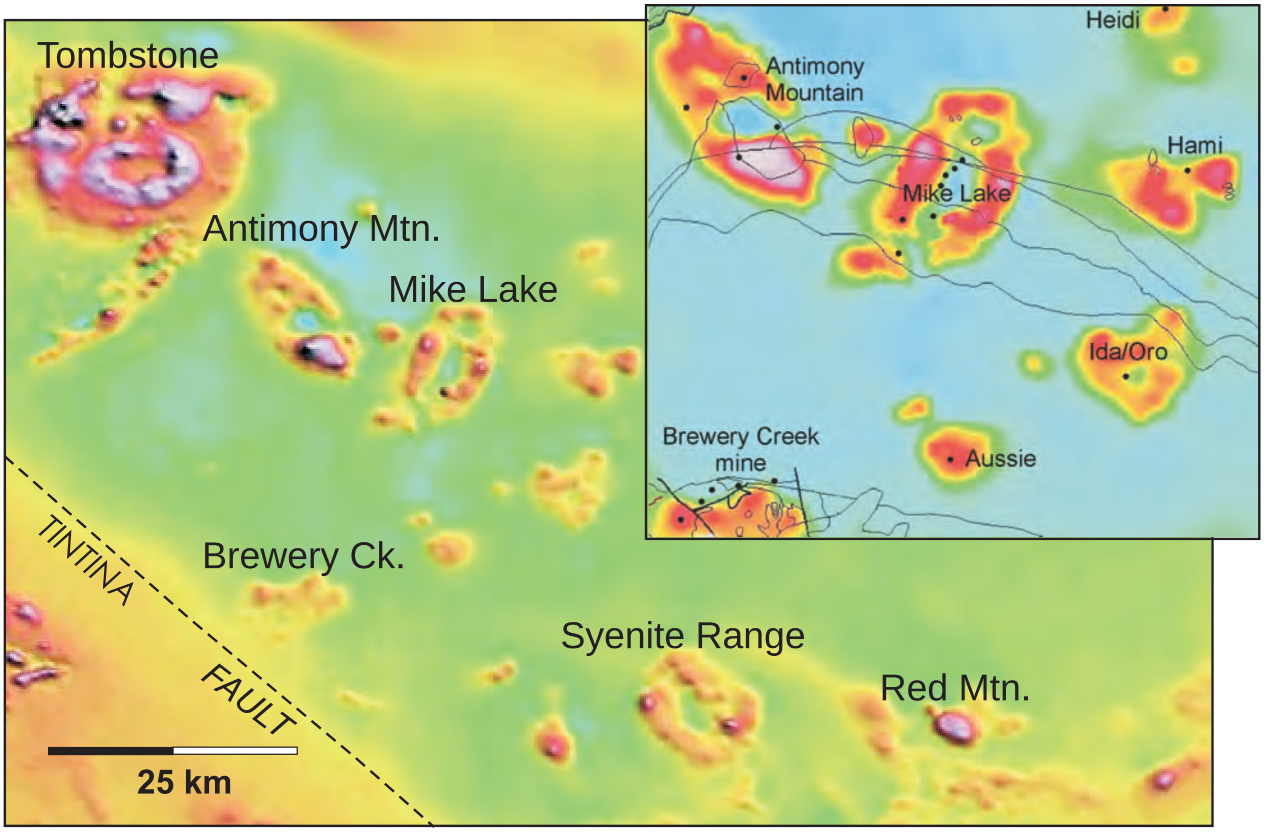

FIGURE 16. Residual total magnetic intensity from airborne aeromagnetic data indicate that, despite their low magnetic response, many plutons can be identified aeromagnetically by the positive signatures generated by magnetic hornfels zones that likely develop from contact metamorphic pyrrhotite aureoles. The results are doughnut-shaped features with lows generated by the ilmenite-series plutons forming the "holes". The inset shows detailed magnetic features in the Mike Lake area, with the black dots indicating mineral occurrences and the lines indicating geological contacts. Notably, mineralization at the Heidi, Hami, Ida/Oro, and Aussie occurrences are associated with large magnetic expressions, but little or no outcrop of plutonic rocks. These occurrences, as well as the Red Mountain occurrence, likely represent roof zones above the tops of the mostly unexposed plutons.

et al., 2003) and orogenic (Goldfarb et al., 2000, 2004, 2005; Groves et al., 2003). Even Central Asian gold deposits, such as Muruntau (Sillitoe, 1991; Wall et al., 2004) and Jilau (Cole et al., 2000), have been considered to be RIRGS. It is important, therefore, that a clear set of characteristics that distinguish RIRGS from orogenic gold deposits be established.

Areas of High Potential in Canada

Good potential still remains in central Yukon, where numerous plutonic systems intruding the continental margin were originally (ca. 1994) assessed for only their intrusion-hosted ores with little effort directed towards hornfels-hosted ores. Although the RIRGS classification still requires improvement, significant advances in understanding were made during a time of limited exploration activity (1998–2003) and the fruits of that research may not have been effectively applied. As well, little effort has been directed toward evaluating roof zones or toward the search for unroofed plutons.

Many RIRGS prospects still have considerable exploration potential, each with numerous untested drill targets. Scheelite Dome, in particular, has a 10 km-long, >100 ppb Au soil anomaly that has not been fully explored. Clear Creek's Bear Paw zone, with drill intersections of 2.3 g/t Au over 31.8 m, remains open in many directions. Dublin Gulch's Eagle zone, currently at 72 t (2.3 million oz) of contained Au, remains open and three other zones of sheeted veins are yet to be fully drill tested.

In southeastern British Columbia, most effort has been directed towards large solitary veins, but potential also exists in targeting bulk tonnage deposits in pluton cupolas. The greatest potential in BC exists with the Bayonne plutonic suites, but plutons tend to be large, so smaller stocks or apophyses should be considered.

Exploration for RIRGS in Archean and Proterozoic terranes has been limited, and perhaps rightfully so considering the lack of appropriate tectonic environments for their formation or preservation during these time. However, the value of Bi-Te signatures as Au pathfinders for intrusion-related systems in these environments appear to have been broadly considered.

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References

Alexco Resources Corp., 2006, Alexco Announces Results from Brewery Creek: Yukon Diamond Drilling, News Release. http://www.alexcoresource.com/s/NewsReleases.asp.

Allen, T.L., Hart, C.J.R., and Marsh, E.E., 1999, Placer gold and associated heavy minerals of the Clear Creek drainage, central Yukon: Past to present, *in* Roots, C.F., and Emond, D.S., ed., Yukon exploration and geology 1998: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 197–214.

Anderson, R.G., 1983, Selwyn Plutonic Suite and its relationship to tungsten mineralization, southeastern Yukon and District of Mackenzie: Geological Survey of Canada, Current Research, Paper 83-1B, p. 151–163.

—— 1987, Plutonic rocks in the Dawson map area, Yukon Territory: Geological Survey of Canada, Current Research, Paper 87-1A, p. 689–697.

—— 1988, An overview of some Mesozoic and Tertiary plutonic suites and their associated mineralization in the northern Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 96–113.

Baker, E.M., and Tullemans, F.J., 1990, Kidston gold deposit: Australasian Institute of Mining and Metallurgy, Monograph 14, p. 1461–1465.

Baker, T., 2002, Emplacement depth and carbon dioxide-rich fluid inclusions in intrusion-related gold deposits: Economic Geology, v. 97, p. 1111–1117.

Baker, T., and Lang, J.R., 2001, Fluid inclusion characteristics of intrusion-related gold mineralization, tombstone-Tungsten magmatic belt, Yukon Territory, Canada: Mineralium Deposita, v. 36, p. 563–582.

Bakke, A.A., 1995, The Fort Knox "porphyry" gold deposit: Structurally controlled stockwork and shear quartz vein, sulphide-poor mineralization hosted by Late Cretaceous pluton, east-central Alaska: Canadian Institute of Mining and Metallurgy, Special Volume 46, p. 795–802.

Bakke, A., Morrel, B., Odden, J., Bergstron, T., and Woodman, J., 2000, Kinross Gold USA's activities in the Fairbanks mining district, K2K: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 89–98.

Blevin, P.L., 2004, Redox and compositional parameters of interpreting the granitoids metallogeny of eastern Australia: Implications for gold-rich ore systems: Resource Geology, v. 54, p. 241–252.

Brown, I.J., and Nesbitt, B.E., 1987, Gold-copper-bismuth mineralization in hedenbergitic skarn, Tombstone Mountains, Yukon: Canadian Journal of Earth Sciences, v. 24, p. 2362–2372.

Brown, V.S., Baker, T., and Stephens, J.R., 2002, Ray Gulch tungsten skarn, Dublin Gulch, central Yukon: Gold-tungsten relationships in intrusion-related ore systems and implications for gold exploration, *in* Emond, D.S., Weston, L.H., and Lewis, L.L., ed., Yukon exploration and geology 2001: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 259–268.

Burnham, C.W., 1979, Magma and hydrothermal fluids, in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits, 2nd edition: New York, Wiley, p. 71–136.

Burnham, C.W., and Ohmoto, H., 1980, Late-stage processes of felsic magmatism: Kozan Chishitsu (Mining Geology), v. 8, p. 1–11.

Candela, P.A., and Blevin, L.P., 1995, Do some miarolitic cavities preserve evidence of magmatic volatile phase permeability?: Economic Geology, v. 90, p. 2310–2316.

Candela, P.A., and Piccoli, P.M., 2005, Magmatic processes in the development of porphyry-type ore systems: Economic Geology 100th Anniversary Volume, p. 25–38.

Cole, A., Wilkinson, J.J., Halls, C., and Serenko, T.J., 2000, Geological characteristics, tectonic setting, and preliminary interpretations of the Jilau gold-quartz vein deposit, Tajikistan: Mineralium Deposita, v. 35, p. 600–618.

Diment, R., and Craig, S., 1999, Brewery Creek gold deposit, central Yukon, *in* Roots, C.F., and Emond, D.S., ed., Yukon exploration and geology 1998: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 225–230.

Ebert, S., Miller, L., Petsel, S., Dodd, S., Kowalczyk, P., Tucker, T.L., and Smith, M.T., 2000, Geology, mineralization, and exploration at the Donlin Creek project, southwestern Alaska: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 99–114.

Ebert, S.W., Baker, T., and Spencer, R.J., 2003, Fluid inclusion studies at the Donlin Creek gold deposit, Alaska: Possible evidence for reduced porphyry-Au to sub-epithermal transition: Society for Geology Applied to Mineral Deposits, Proceedings of the Seventh Biennial Meeting, Athens, August 24–28, p. 263–266.

Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn Deposits: Economic Geology, 75th Anniversary Volume, p. 317–391.

Farmer, G.L., Mueller, S., Marsh, E., Goldfarb, R.J., and Hart, C.J.R., 2000, Isotopic evidence on sources of Au-related mid-Cretaceous Tombstone Plutonic Suite granitic rocks, Clear Creek district, Yukon [abs.]: Geological Society of America, Cordilleran Section Abstracts with Programs, v. 32, p. A-13.

Flanigan, B., Freeman, C., Newberry, R., McCoy, D., Hart, C., 2000, Exploration models for mid and Late Cretaceous intrusion-related gold deposits in Alaska and the Yukon Territory, Canada, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., and others, eds., Geology and ore deposits 2000: The Great basin & beyond, Geological Society of Nevada, Symposium Proceedings, p. 591–614.

Geological Survey of Canada, 1978, Regional stream sediment and water geochemical reconnaissance data, central Yukon Territory, NTS 106D and parts of 106C, E and F; 116A and part of 116H; and parts of 116B, C, F and G: Geological Survey of Canada, Open File 518, 519, and 520, 42 maps, scale: 1:250,000.

—— 1990, Regional stream sediment and water geochemical reconnaissance data, Yukon Territory (106D; parts of 106C, 106E, 106F): 42 maps, Geological Survey of Canada, Open File 2175, 42 maps, scale: 1:250,000, 210 p.

—— 1991, Regional stream sediment and water geochemical reconnaissance data, Yukon Territory (116 B, parts of 116 C, 116 F & 116 G): 41 maps, Geological Survey of Canada, Open File 2365, 41 maps, scale: 1:250,000, p. 198.

Goldfarb, R., Hart, C., Miller, M, Miller, L., Farmer, G.L., and Groves, D., 2000, The Tintina Gold Belt: A global perspective: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 5–34.

Goldfarb, R.J., Ayuso, R., Miller, M.L., Ebert, S.W., Marsh, E.E., Petsel, S.A., Miller, L.D., Bradley, D., Johnson, C., and McClelland, W., 2004, The Late Cretaceous Donlin Creek deposit, southwestern Alaska-controls on epizonal formation: Economic Geology, v. 99, p. 643–671.

Goldfarb, R.J., Bake, T., Dubé, B., Groves, D.I., Hart, C.J.R., and Gosselin, P., 2005, Distribution, character, and genesis of gold deposits in metamorphic terranes: Economic Geology, 100th Anniversary Volume, p. 407–450.

Gordey, S.P., and Anderson, R.G., 1993, Evolution of the northern Cordilleran miogeocline, Nahanni map area (105I), Yukon and Northwest Territories: Geological Survey of Canada, Memoir 248, 214 p.

Groves, D.I., Goldfarb, R.J., Robert, F., and Hart, C.J.R., 2003, Gold deposits in metamorphic belts: Overview of current understanding, outstanding problems, future research, and exploration significance: Economic Geology, v. 98, p. 1–29.

Hart, C.J.R., 2005, Classifying, distinguishing and exploring for intrusion-related gold systems: The Gangue: Newsletter of the Geological Association of Canada Mineral Deposits Division, v. 87, p. 1, 4–9.

Hart, C.J.R., and Goldfarb, R.J., 2005, Distinguishing intrusion-related from orogenic gold systems: Proceedings of the 2005 New Zealand Minerals Conference, Auckland, November 13–16, p. 125–133.

Hart, C.J.R., Baker, T., and Burke, M., 2000a, New exploration concepts for country-rock hosted, intrusion-related gold systems, Tintina Gold Belt:

British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 145–172.

Hart, C.J.R., Baker, T., Lindsay, M.J., Oliver, N.H.S., Stephens, J.R., and Mair, J.L., 2000b, Structural controls on Tombstone Plutonic Suite gold deposits, Tintina Gold Belt, Yukon [abs.]: Geological Society of America Abstracts with Programs, Cordilleran Section, v. 32, p. 6.

Hart, C.J.R., McCoy, D., Goldfarb, R.J., Smith, M., Roberts, P., Hulstein, R., Bakke, A.A., and Bundtzen, T.K., 2002, Geology, exploration and discovery in the Tintina gold province, Alaska and Yukon: Society of Economic Geologists, Special Publication 9, p. 241–274.

Hart, C.J.R., Goldfarb, R.J., Lewis, L.L., and Mair, J.L., 2004a, The Northern Cordillera Mid-Cretaceous Plutonic Province: Ilmenite/magnetite-series granitoids and intrusion-related mineralisation: Resource Geology, v. 54, n. 3, p. 253–280.

Hart, C.J.R., Villeneuve, M.E., Mair, J.L., Goldfarb, R.J., Selby, D., Creaser R.A., and Wijns, C., 2004b, Comparative U-Pb, Re-Os, and Ar-Ar geochronology of mineralizing plutons in Yukon and Alaska [abs.]: The University of Western Australia Centre for Global Exploration, Publication 33, p. 347–349.

Hart, C.J.R., Mair, J.L., Goldfarb, R.J., and Groves, D.I., 2005, Source and redox controls of intrusion-related metallogeny, Tombstone-Tungsten Belt, Yukon, Canada: Transactions of the Royal Society of Edinburgh: Earth Science, v. 95, p. 339–356.

Hitchins, A.C., and Orssich, C.N., 1995, The Eagle zone gold-tungsten sheeted vein porphyry deposit and related mineralization, Dublin Gulch, Yukon Territory: Canadian Institute of Mining and Metallurgy, Special Volume 46, p. 803–810.

Hollister, V.F., 1992, On a proposed plutonic porphyry gold deposit model: Nonrenewable Resources, v. 1, p. 293–302.

Hulstein, R., Zuran, R., Carlson, C.G., and Fields, M., 1999, The Scheelite dome gold project, central Yukon, *in* Roots, C.F., and Emond, D.S., ed., Yukon exploration and geology 1998: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 243–248.

Ishihara, S., 1981, The granitoid series and mineralization: Economic Geology 75th Anniversary Volume, p. 458–484.

Jones, B.K., 1992, Application of metal zoning to gold exploration in porphyry copper systems: Journal of Geochemical Exploration, v. 43, n. 2, p. 127–155.

Lang, J.R., 2001, Regional and system-scale controls on the formation of copper and or gold magmatic-hydrothermal mineralization: University of British Columbia Mineral Deposit Research Unit, Special Publication 2, 115 p.

Lang, J.R., and Baker, T., 2001, Intrusion-related gold systems: the present level of understanding: Mineralium Deposita, v. 36, p. 477–489.

Lang, J.R., Baker, T., Hart, C.J.R., and Mortensen, J.K., 2000, An exploration model for intrusion-related gold systems: Society of Economic Geology Newsletter, v. 40, p. 1, 6–15.

Lennan, W.B., 1983, Ray Gulch tungsten skarn deposit, Dublin Gulch area, central Yukon: Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 37, p. 245–254.

Leveille, R.A., Newberry, R.J., and Bull, K.F., 1988, An oxidation state-alkalinity diagram for discriminating some gold-favorable plutons; an empirical and phenomenalogical approach [abs.]: Geological Society of America Abstracts with Programs, v. 20, p. 142.

Lindsay, M.J., Baker, T., Oliver, N.H.S., Diment, R., and Hart, C.J.R., 2000, The magmatic and structural setting of the Brewery Creek gold mine, central Yukon, *in* Emond, D., and Weston, L., ed., Yukon exploration and geology 1999: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 219–227.

Logan, J., Lefebure, D., and Cathro, M., 2000, Plutonic related gold-quartz veins and their potential in British Columbia: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 197–225.

Lynch, J.V.G., 1989, Large scale hydrothermal zoning reflecting in tetrahedrite-freibergite solid solution, Keno Hill Ag-P-Zn district, Yukon: Canadian Mineralogist, v. 27, p. 383–400.

Mair, J.L., 2004, Tectonic setting, magmatism and magmatic-hydrothermal systems at Scheelite Dome, Tombstone Gold Belt, Yukon: Critical constraints on intrusion-related gold systems: Unpublished Ph.D. thesis, Perth, University of Western Australia, 197 p.

Mair, J.L., Hart, C.J.R., Goldfarb, R.J., O'Dea, M., and Harris, S., 2000, Geology and metallogenic signature of gold occurrences at Scheelite Dome, Tombstone gold belt, Yukon, in Emond, D., and Weston, L., ed., Yukon exploration and geology 1999: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 165–176.

Mair, J.L., Goldfarb, R.J., Johnson, C.A., Hart, C.J.R., and Marsh, E.E., 2006a, Geochemical constraints on the genesis of the Scheelite Dome intrusion-related gold deposit, Tombstone Gold Belt, Yukon, Canada: Economic Geology, v. 101, p. 523–553.

Mair, J.L., Hart, C.J.R., and Stephens, J., 2006b, Deformation history of the northwestern Selwyn Basin, Yukon, Canada: Implications for orogen evolution and mid-Cretaceous magmatism: Geological Society of America Bulletin, v. 118, p. 304–323.

Maloof, T.L., Baker, T., and Thompson, J.F.H., 2001, The Dublin Gulch intrusion-hosted deposit, Tombstone Plutonic Suite, Yukon Territory, Canada: Mineralium Deposita, v. 36, p. 583–593.

Marsh, E.E., Hart, C.J.R., Goldfarb, R.J., and Allen, T.L., 1999, Geology and geochemistry of the Clear Creek gold occurrences, Tombstone gold belt, central Yukon Territory,*in* Roots, C.F., and Emond, D.S., ed., Yukon exploration and geology 1998: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 185–196.

Marsh, E.E., Goldfarb, R.J., Hart, C.J.R., and Johnson, C.A., 2003, Geology and geochemistry of the Clear Creek intrusion-related gold occurrences, Tintina gold province, Yukon, Canada: Canadian Journal of Earth Sciences, v. 40, n. 5, p. 681–699.

McCoy, D., Newberry, R.J., Layer, P.W., DiMarchi, J.J., Bakke, A.A., Masterman, J.S., and Minehane, D.L., 1997, Plutonic-related gold deposits of interior Alaska: Economic Geology, Monograph 9, p. 191–241.

McCoy, D., Newberry, R.J., Severin, K., Marion, P., Flanigan, B., and Freeman, C., 2002, Paragenesis and metal associations in interior Alaska gold deposits: An example from the Fairbanks district: Mining Engineering, v. 54, 1, p. 33–38.

McCuaig, T.C., Behn, M., Stein, H.J., Hagemann, S.G., McNaughton, N.J., Cassidy, K.F., Champion, D.C., and Wyborn, L., 2001, The Boddington gold mine: A new style of Archaean Au-Cu deposit [abs.]: Australian Geological Survey Organisation, 4th International Archaean Symposium, 2001/37, p. 453–455.

McLeod, M.J., and McCutcheon, S.R., 2000, Gold environments in New Brunswick: Map plate 2000-8: New Brunswick Dept. of Natural Resources and Energy, Minerals and Energy Division: scale: 1:500,000.

Meinert, L.D., 1998, A review of skarns that contain gold, *in* Lentz, D.R., ed., Mineralized porphyry/skarn systems: Mineralogical Association of Canada, Short Course Series, v. 26, p. 359–414.

Mortensen, J.K., Hart, C.J.R., Murphy, D.C., Heffernan, S., Tucker, T.L., and Smith, M.T., 2000, Temporal evolution of Early and Mid-Cretaceous magmatism in the Tintina gold belt: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 49–58.

Mungall, J.E., 2002, Roasting the mantle: Slab melting and the genesis of major Au and Au-rich Cu deposits: Geology, v. 30, p. 915–918.

Murphy, D.C., 1997, Geology of the McQuesten River region, northern McQuesten and Mayo map areas, Yukon Territory: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Bulletin 6, 95 p.

Mustard, R., 2001, Granite-hosted gold mineralization at Timbarra, northern New South Wales: Mineralium Deposita, v. 36, p. 542–562.

Mustard, R., Ulrich, T., Kamenetsky, V.S., and Mernagh, T., 2006, Gold and metal enrichment in natural granitic melts during fractional crystallization: Geology, v. 34, p. 85–88.

Newberry, R.J., McCoy, D.T., and Brew, D.A., 1995, Plutonic-hosted gold ores in Alaska: Igneous versus metamorphic origins: Resource Geology, Special Issue 18, p. 57–100.

O'Dea, M., Carlson, G., Harris, S., Fields, M., Tucker, T.L., and Smith, M.T., 2000, Structural and metallogenic framework for the Scheelite Dome Deposit, Yukon Territory: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 115–129.

Poulsen, K.H., 1996, Carlin-type gold deposits and their potential occurrence in the Canadian Cordillera, Geological Survey of Canada, Current Research, Report 1996-A, p. 1–9.

Poulsen, K.H., Mortensen, J.K., and Murphy, D.C., 1997, Styles of intrusion-related gold mineralization in the Dawson-Mayo area, Yukon Territory: Geological Survey of Canada, Current Research, Report: 1997-A/B, p. 1–10.

Rhys, D., DiMarchi, J., Smith, M., Friesen, R., and Rombach, C., 2003, Structural setting, style and timing of vein-hosted gold mineralization at the Pogo Deposit, east central Alaska: Mineralium Deposita, v. 38, p. 863–875.

Robert, F., 2001, Syenite-associated disseminated gold deposits in the Abitibi greenstone belt, Canada: Mineralium Deposita, v. 36, p. 503–516.

Rowins, S.M., 2000, Reduced porphyry copper-gold deposits: A new variation on an old theme: Geology, v. 28, p. 491–494.

Selby, D., Creaser, R.A., and Hart, C.J.R., 2001, Timing relationship between plutonism and gold mineralization: Re-Os molybdenite study of the reduced intrusion-related gold deposits of the Tombstone Plutonic Suite, Yukon and Alaska [abs.]: Joint Annual Geological Association of canada—Mineralogical Association of Canada, Abstracts and Program, St. Johns, Newfoundland, May 27-30, p. 134.

Sillitoe, R.H., 1991, Intrusion-related gold deposits, *in* Foster, R.P., ed., Gold metallogeny and exploration: Glasgow, Blackie, p. 165–209.

—— 1995, Gold-rich porphyry copper deposits: Geological model and exploration implications: Geological Association of Canada, Special Paper 40, p. 465– 478.

Sillitoe, R.H., and Thompson, J.F.H., 1998, Intrusion-related vein gold deposits: Types, tectono-magmatic settings, and difficulties of distinction from orogenic gold deposits: Resource Geology, v. 48, p. 237–250.

Sinclair, W.D., 2007, Porphyry deposits, *in* Goodfellow, W.D., ed., Mineral deposits of Canada: A synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 223-243.

Smit, H., Sieb, M., and Swanson, C., 1996, The Dublin Gulch intrusive-hosted gold deposit: British Columbia Geological Survey, Cordilleran Round Up 1996, Short Course Notes, p. F.3–F.13.

Smith, M., Thompson, J., Bressler, J., Layer, P., Mortensen, J., Abe, I., and Takaoka, H., 1999, Geology of the Liese zone, Pogo property, East-Central Alaska: Society of Economic Geology Newsletter, v. 38, p. 1, 12–21.

Stephens, J.R., Oliver, N.H.S., Baker, T., and Hart, C.J.R., 2000, Structural evolution and controls on gold mineralization at Clear Creek, Yukon, *in* Emond, D., and Weston, L., ed., Yukon exploration and geology 1999: Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 151–163.

Stephens, J.R., Mair, J.L., Oliver, N.H.S., Hart, C.J.R., Baker, T., Blenkinsop, T.G., Vearncombe, J.R., and Reddy, S.M., 2004, Structural and mechanical controls on intrusion-related deposits of the Tombstone gold belt, Yukon, Canada, with comparisons to other vein-hosted ore-deposit types: Journal of Structural Geology, v. 26, p. 1025–1041.

Thompson, J.F.H., and Newberry, R.J., 2000, Gold deposits related to reduced granitic intrusions: Society of Economic Geologists, Reviews 13, p. 377–400.

Thompson, J.F.H., Sillitoe, R.H., Baker, T., Lang, J.R., and Mortensen, J.K., 1999, Intrusion-related gold deposits associated with tungsten-tin provinces: Mineralium Deposita, v. 34, p. 323–334.

Tucker, T.L., and Smith, M.T., 2000, The Tintina Gold Belt: Concepts, exploration, and discoveries: British Columbia and Yukon Chamber of Mines, Special Volume 2, p. 225

Wall, V.J., Graupner, T., Yantsen, V., Seltmann, R., and Hall, G.C., 2004, Muruntau, Uzbekistan: A giant thermal aureole gold (TAG) system [abs.]: Perth, University of Western Australia, Centre for Global Metallogeny, Extended Abstracts, v. 33, p. 199–203.

Witt, W.K., 2001, Tower Hill gold deposits, Western Australia: An atypical, multiply deformed Archaean gold-quartz deposit: Australian Journal of Earth Sciences, v. 48, p. 81–99.